Post-disaster geotechnical response for hilly terrain: a case study from the Canterbury Earthquake Sequence

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Abstract

Case study analysis of the 2010-2011 Canterbury Earthquake Sequence (CES), which particularly impacted Christchurch City, New Zealand, has highlighted the value of practical, standardised and coordinated post-earthquake geotechnical response guidelines for earthquake-induced landslides in urban areas. The 22nd February 2011 earthquake, the second largest magnitude event in the CES, initiated a series of rockfall, cliff collapse and loess failures around the Port Hills which severely impacted the south-eastern part of Christchurch. The extensive slope failure induced by the 22nd February 200 earthquake was unprecedented; and ground motions experienced significantly exceeded the probabilistic seismic hazard model for Canterbury.

Earthquake-induced landslides initiated by the 22nd February 2011 earthquake posed risk to life safety, and caused widespread damage to dwellings and critical infrastructure. In the immediate aftermath of the 22nd February 2011 earthquake, the geotechnical community responded by deploying into the Port Hills to conduct assessment of slope failure hazards and life safety risk. Coordination within the voluntary geotechnical response group evolved rapidly within the first week post-earthquake. The lack of pre-event planning to guide coordinated geotechnical response hindered the execution of timely and transparent management of life safety risk from coseismic landslides in the initial week after the earthquake.

Semi-structured interviews were conducted with municipal, management and operational organisations involved in the geotechnical response during the CES. Analysis of interview dialogue highlighted the temporal evolution of priorities and tasks during emergency response to coseismic slope failure, which was further developed into a phased conceptual model to inform future geotechnical response. Review of geotechnical responses to selected historical earthquakes (Northridge, 1994; Chi-Chi, 1999; Wenchuan, 2008) has enabled comparison between international practice and local response strategies, and has emphasised the value of pre-earthquake preparation, indicating the importance of integration of geotechnical response within national emergency management plans. Furthermore, analysis of the CES and international earthquakes has informed pragmatic recommendations for future response to coseismic slope failure.

Recommendations for future response to earthquake-induced landslides presented in this thesis include: the integration of post-earthquake geotechnical response with national Civil Defence and Emergency Management; pre-earthquake development of an adaptive management structure and standard slope assessment format for geotechnical response; and emergency management training for geotechnical professionals. Post-earthquake response recommendations include the development of geographic sectors within the area impacted by coseismic slope failure, and the development of a GIS database for analysis and management of data collected during ground reconnaissance. Recommendations provided in this thesis aim to inform development of national guidelines for geotechnical response to earthquake-induced landslides in New Zealand, and prompt debate concerning international best practice.

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Chapter One: Introduction

1.1 Context

Earthquake-induced slope failures can be catastrophic secondary hazards which contribute to the destruction and damage produced during and after an earthquake. Slope failures can include falls, slides, flows and complex movements which can be destructive and disruptive to critical infrastructure (e.g. energy and transportation routes, telecommunication, water and sewage reticulation, etc.), buildings and can present threats to life safety (Crozier and Glade 2004; Hincks et al. 2013). The 2008 M_w 8.0 Wenchuan earthquake in Sichuan, China provides an example of the impact of coseismic slope failure to life safety, where over a quarter of the lives lost during the earthquake were attributed to earthquake-induced landslides (Cui et al. 2011). The degree of impact from earthquake-induced slope failure hazard is influenced by characteristics such the failure mechanism, the volume of material, the rate of failure, the size of area exposed to inundation or evacuation of material, and the management techniques implemented to control impact (Hincks et al. 2013).

Management of risk from coseismic slope failures can be achieved pre-earthquake through hazard mapping and analysis, implementation of land use regulations, installation of engineering stabilisation and protection works, slope monitoring, early warning systems and community education (Crozier 2004; Hincks et al. 2013). Risk is defined as the measure of probability and severity of an adverse affect to life, health, property, or the environment (ISSMGE 2004). It is known from previous earthquakes that the impact from coseismic slope failures can be widespread, and if unplanned for can disrupt post-earthquake response and relief efforts. The M_W 7.6 earthquake in Kashmir, Pakistan, in 2005 which caused extensive coseismic landsliding which disrupted relief aid provides an example that emphasises the necessity for management of earthquake-induced slope failures during emergency response (Peiris et al. 2006). Reviewed literature of earthquakes around the world, has indicated that there are no international guidelines outlining best practice for effective and efficient post disaster management of earthquake-induced slope failures.

Many of the current strategies for landslide risk management have been developed as a pre-disaster framework for thorough quantitative or qualitative assessment (Fell et al. 2005). Very little research has examined how to best implement rapid qualitative risk assessment of coseismic slope failure post-earthquake when assessment is predominately reliant on field observations, and detailed information of the mechanisms of failure is lacking or non-existent. Furthermore, rapid execution of post-earthquake risk management strategies are based on the assessment outcome which is typically focused on risk to life safety.

In the aftermath of an earthquake the contribution of scientists and engineers in the evaluation of risk is important, however the interface between engineers and post-earthquake emergency management is often unclear (Brunsdon 2012). In some countries procedures have been developed for post-earthquake building assessments however, typically management of geotechnical response has not been as thoroughly addressed. Because of this, in the aftermath of an earthquake there can be a requirement for coordination to develop within the response from geotechnical professionals which can hinder the efficiency of emergency response and risk assessment. A framework has been developed by the Californian Applied Technology Council (ATC) which has addressed this issue by incorporating the assessment of slope failures with the execution of post-earthquake building safety evaluation (Applied Technology Council 1995). Similarly, guidelines for building safety evaluation have been developed in New Zealand by the New Zealand Society for Earthquake Engineering. These guidelines provide recommendations for post-earthquake response by structure engineers and building inspectors but do not include a methodology for the assessment of secondary geological hazards such as slope failures (NZSEE 2009).

The high level of seismic hazard and mountainous terrain of New Zealand highlights the requirement for a framework to guide assessment of post-earthquake risk to life safety from coseismic landslides. Between 1840 and 2002 New Zealand experienced at least 22 earthquakes which resulted in widespread and damaging landsliding (Hancox et al. 2002). Recently, the 2010-2011 Canterbury Earthquake Sequence added to this figure and further highlighted the susceptibility of urban areas of New Zealand to coseismic slope failure. Management of the geotechnical response during the 2010-2011 Canterbury Earthquake Sequence (CES) indicates that the timely execution and effective coordination of risk assessment of coseismic slope failures may have been hindered by the lack of preformed guidelines for geotechnical response. Therefore, research is required to examine the response to coseismic slope failures during the CES in order to identify underlying issues that impeded the geotechnical response.

The response to slope failure that occurred during the CES provides a case study example of the requirements of post-earthquake geotechnical response. Comprehensive analysis of the CES provides insight into the fundamental priorities and tasks that relate to geotechnical response management and landslide risk management. Retrospective analysis of the post-earthquake landslide response mechanisms during the CES can inform pre-earthquake planning to guide emergency response to future coseismic slope failure. This thesis examines the geotechnical response to the CES, and provides a comprehensive appraisal indicating methods for improving future emergency response to earthquake-induced landslides.

1.2 Research Objectives

The goal of this research is to analyse and review the approach to post-earthquake risk assessment of landslides to inform recommendations for pre-earthquake geotechnical response planning. Several international earthquakes and the Canterbury earthquake sequence will be used as case studies to inform this analysis.

The objectives for this research are:

- Examine the post-earthquake geotechnical response and management of earthquake-induced slope failure implemented during the 2010-2011 Christchurch earthquake sequence,
- Develop a conceptual model of the information needs throughout time for emergency geotechnical response to the Canterbury Earthquake Sequence,
- Provide comparison between historical international earthquakes and the Canterbury Earthquake Sequence to identify similarities and differences between response strategies,
- Develop a series of recommendations for geotechnical response to earthquakes-induced landslides to inform future earthquake response planning and preparation.

1.3 Research Methodology

The research methodology used in this thesis is a mixed-method approach with four main phases:

1. A comprehensive literature review of major historical global earthquakes where secondary geotechnical hazards occurred in populated areas. This gave insight into the methods of geotechnical response to coseismic landslide hazards implemented by government organisations and geotechnical professionals internationally. Furthermore, the review of literature enabled common practice for geotechnical response to be identified.

2. A series of interviews conducted with municipal, emergency management, and geotechnical professionals who were operationally involved with the geotechnical response that took place during the 2010-2011 Canterbury Earthquake Sequence. Participants were selected on the basis of their professional roles and participated in the research on a voluntary basis. Interviews were semi-structured and guided by a series of prepared questions, with the intention that additional questions may be added by the interviewer to elicit further enquiry as the interview progressed.

3. An analysis of interviews was undertaken to identify recurrent themes and examine the temporal evolution of the geotechnical response to the 2010-2011 Canterbury Earthquake Sequence. This timeline allowed review of the changes in roles and response requirements associated with management of landslide hazards. Through this, the geotechnical response the CES was compared to international earthquakes.

4. Discussion regarding the analysis of the Canterbury Earthquake Sequence case study and historical earthquakes reviewed in literature has informed a series of recommendations developed to guide future post-earthquake response and pre-event planning.

Further detail on the research methodology is provided in Chapter Two.

1.4 The Canterbury Earthquake Sequence

The initiating earthquake in the Canterbury Earthquake Sequence (CES) occurred at 4:35am on the 4th September 2010, with a magnitude M_W 7.1. The earthquake was followed by a progression of aftershocks which propagated eastward from the initial rupture (Figure 1.1). Several of the aftershocks in the sequence initiated slope failures in the Port Hills, which are located south of Christchurch city and in 2008 had a population >58,000 people (NZ Parliment Library 2009). These aftershocks included the 22nd February, 16th April, 13th June and 23rd December 2011 earthquakes. Table 1.1 details comparisons between the geological aspects and casualties from each of these earthquakes. Figure 1.2 presents the progression of aftershocks >M_w 3.0 following the initiating event on the 4th September 2010. In comparison to historical global earthquake sequences, the CES was not atypical, however the time (days, months, years) and distances (between epicentres) between major earthquakes events were generally a shorter than similar international examples (Litchfield and Berryman 2013).

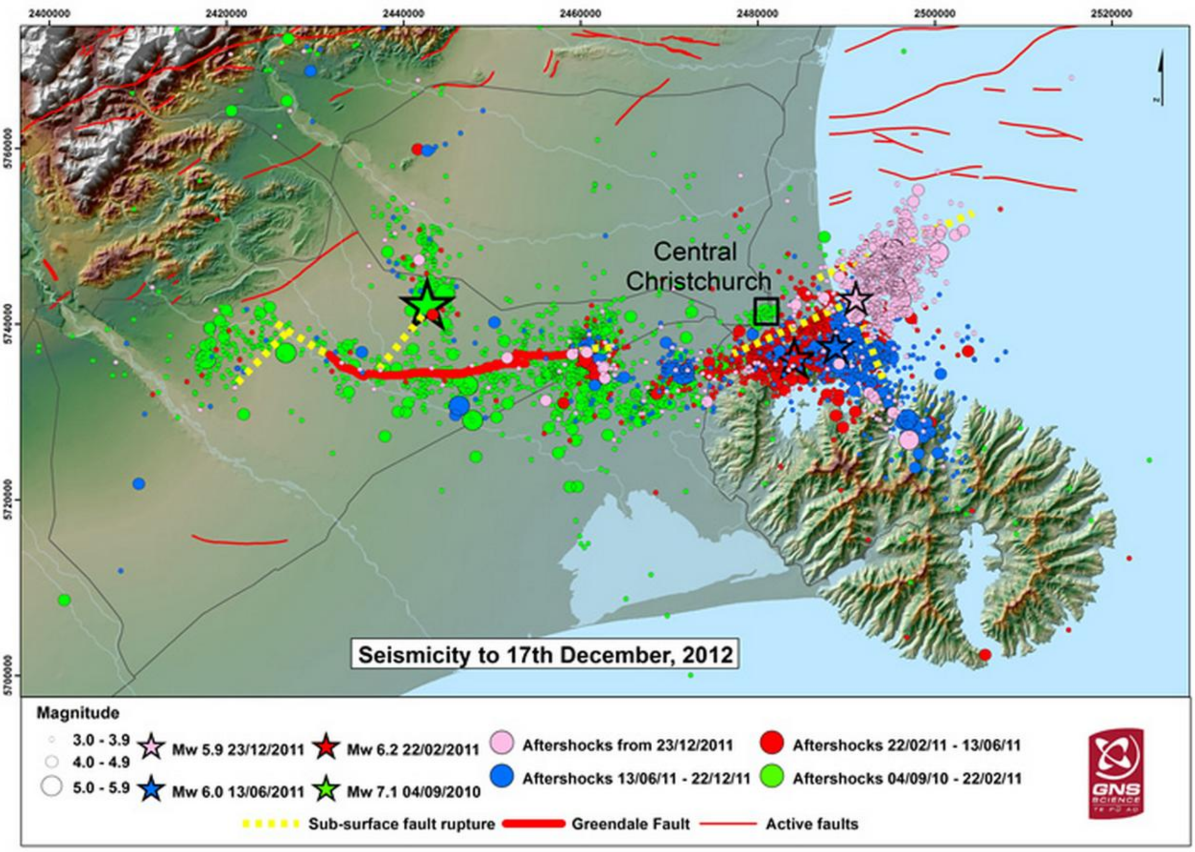


Figure 1.1: Canterbury Earthquake Sequence (GNS Science Ltd 2012)

Table 1.1: Earthquake comparisons (Modified from Berryman, 2012)

	4th September 2012	**22nd February 2011**	**13th June 2011**	**23rd December 2011**
Magnitude M_W	7.1	6.2	6.0	5.9
Epicentre[1]	30 km W	10 km SE	10 km SE	10 km E
Time[2]	04:36	12:51pm	14:20	15:18
Max PGA[3]	0.6g (0.3g CBD)	2.2g (0.8g CBD)	2.2g (0.4g CBD)	0.96g[4] (0.25g CBD)
Causalities	0 fatalities	185 fatalities, (5 fatalities related to slope failures, Dellow et al. 2011)	0 fatalities	0 fatalities

1. Epicentral distances are with respect to Christchurch central business district (CBD)
2. Time is in New Zealand Standard time (NZST) in September 2010 and June 2011, and New Zealand Daylight Saving time in February and December 2011
3. Maximum Peak Ground Acceleration (PGA) in the city – may be horizontal or vertical
4. This was the maximum PGA on 23 December in the earlier and slightly smaller M_W 5.8 event

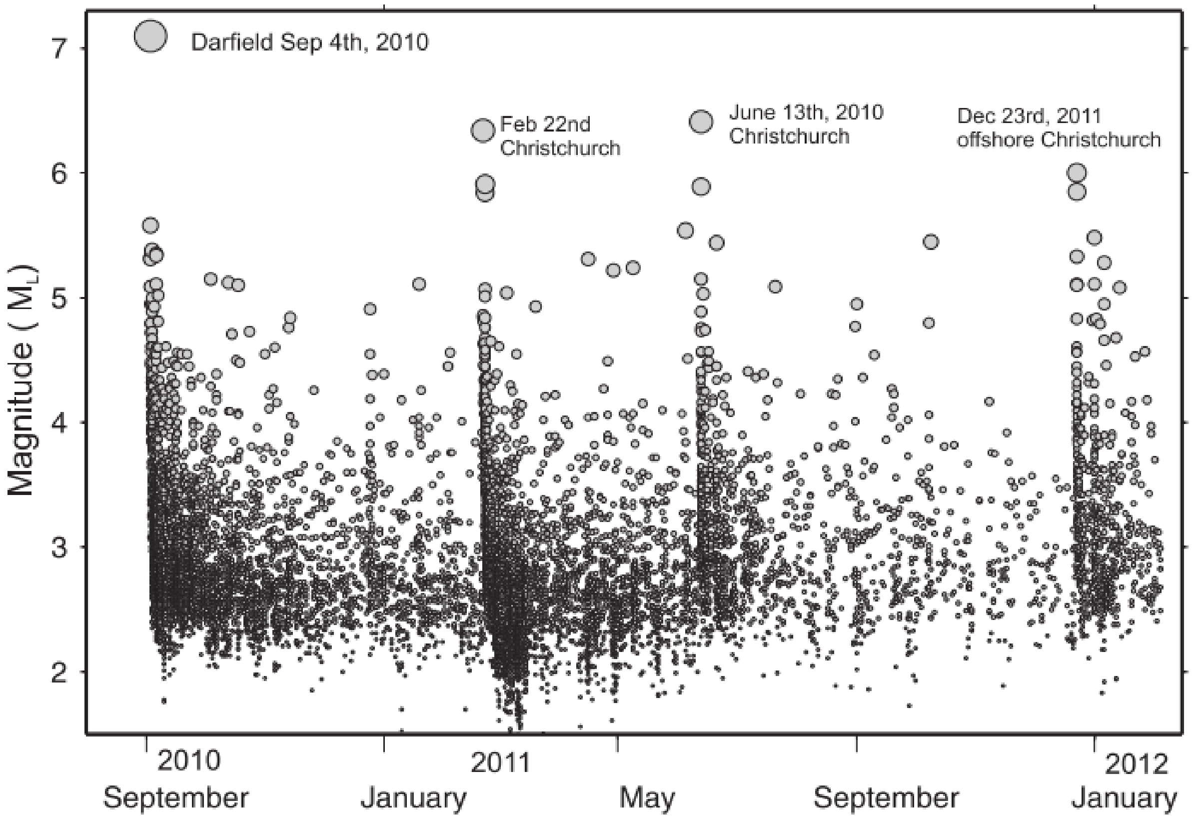


Figure 1.2: Time sequence from September 2010 to February 2012 of earthquakes located in Canterbury. Earthquakes located by GeoNet and plotted as a function of local Magnitude (M_L); (Bannister and Gledhill 2012)

The 4th September 2010 earthquake was located on a previously unrecognised strike-slip fault, later named the Greendale fault, located approximately 30km west of Christchurch Central Business District (CBD). Surface displacement on the Greendale fault was primarily right-lateral strike slip with an average horizontal displacement of approximately 2.5m

(Quigley et al. 2010). Ground motions throughout the central and eastern Christchurch region, including the Port Hills, broadly conformed to the 500-year routine seismic design spectra for the Christchurch urban area according to the New Zealand loading standard, NZ1170.5:2004 (Figure 1.3); (Bradley and Cubrinovski 2011). Ground acceleration reached 0.3g (both in the horizontal and vertical directions) in central Christchurch, and reached 0.6g at Heathcote Valley School GeoNet ground motion station (HVSC) in the Port Hills (Bannister and Gledhill 2012).

Although the 4th September 2010 earthquake exhibited the largest magnitude in the sequence, ground motions were significantly less than subsequent earthquakes and subsequently very little damage was observed in the Port Hills (Macfarlane and Yetton 2013). This indicates that the shaking intensity (ground motion) experienced at ground surface is of greater importance than that of the earthquake magnitude in regard to land damage in hilly terrain (Massey et al. 2012a). A state of local emergency was declared within Christchurch City, Selwyn and Waimakariri districts on the 4th September 2010 hours after the earthquake and remained in place until the 16th September 2010 (Berryman 2012).

The 22nd February 2011 earthquake was situated in close proximity to the Port Hills on a structure named the Port Hills fault and produced vertical ground accelerations at HVSC ranging from 0.4g to 2.2g, and horizontal ground accelerations ranging from 0.3 to 1.4g (Bradley and Cubrinovski 2011; Wood et al. 2011). The 22nd February 2011 earthquake produced ground accelerations which exceeded the 500-year seismic design spectra and vastly exceeded the probabilistic seismic hazard for the Canterbury region (Figure 1.3).

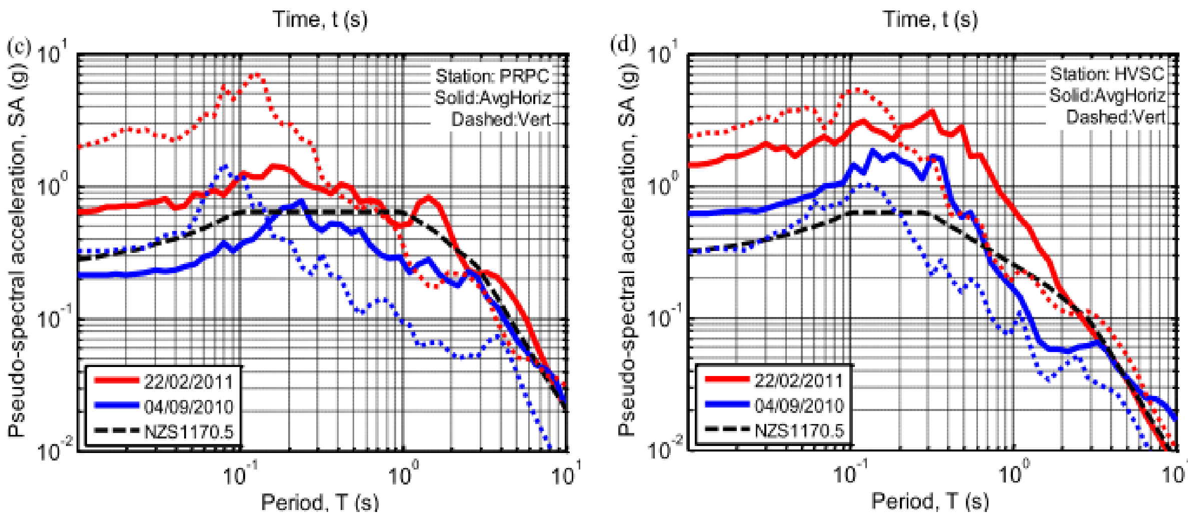


Figure 1.3: Comparison between NZS1170.5 design standard (475-year spectra) and ground motions observed at Pages Road (PRPC) and Heathcote Valley (HVSC) during the 4 September 2010 and 22nd February 2011 earthquakes. Site classes are E and D respectively according to NZ1170.5 (Bradley and Cubrinovski 2011)

Figure 1.4 presents the variation in ground motions across Christchurch, with the second highest recording located at the Pages Road Pumping Station (PRPC). To provide context to these ground motions, prior to the Canterbury Earthquake Sequence the maximum recorded peak ground acceleration in New Zealand was 0.39g (Bradley and Cubrinovski 2011). The high ground accelerations that were produced by the 22nd February earthquake are predicted to be largely responsible for the extent of geotechnical failure on the Port Hills (Massey et al. 2012a). Topographic amplification is also likely to have contributed to the high stress concentration in slope peaks. This was also the case for the 13th June 2011 aftershock where the earthquake epicentres were located in close proximity to the Sumner suburb in the Port Hills and produced high ground accelerations up to 2.2g (Table 1.1). On the 23rd February 2011 the Minster of Civil Defence declared a state of National Emergency which remained enforced until the 30th April 2011 (Mclean et al. 2012). There was no state of emergency declared after the 13th June 2011 earthquake.

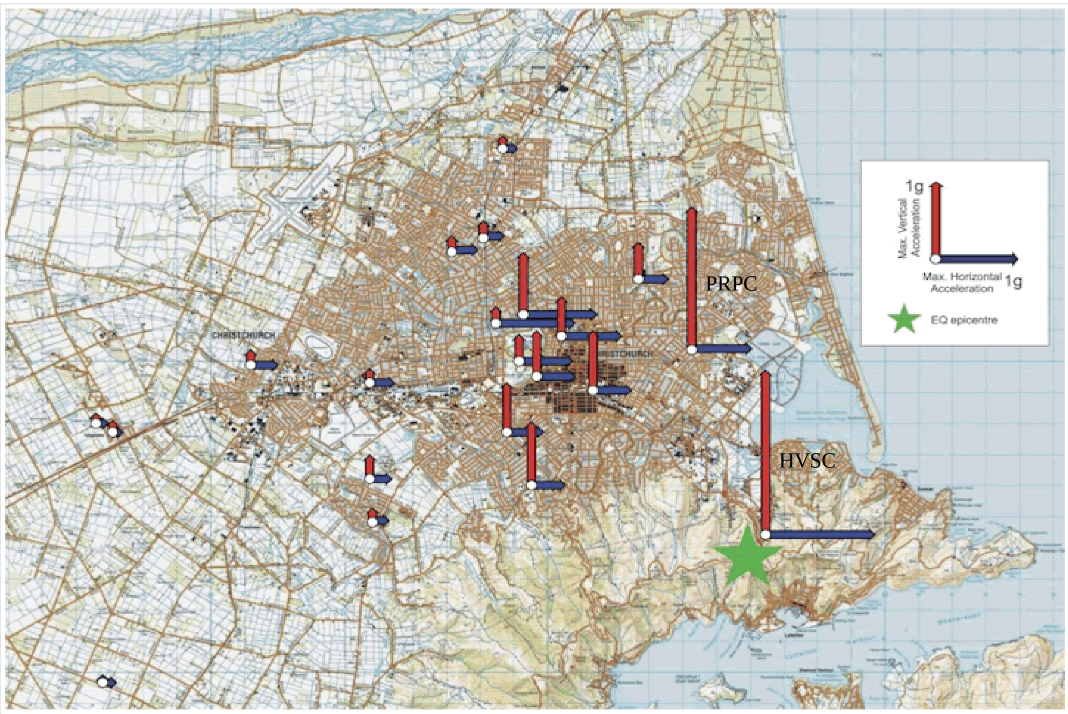


Figure 1.4: Maximum horizontal and peak vertical ground accelerations recorded at GeoNet stations during the 22nd February 2011 earthquake (Massey et al. 2012a)

1.4.1 Geological Context of Port Hills, Christchurch

The majority of slope failures induced by the 2010-2011 Canterbury Earthquake Sequence were located in the Port Hills area in Christchurch. The Port Hills are located on the northern region of the extinct Lyttelton basalt volcano (Hampton 2010). The topography of the Port Hills consists of sea cliffs, gently sloping spurs and ridges, and steep-sided valleys which are formed by rock from the Lyttelton Volcanics Group (Brown and Weeber 1992; Forsyth et al. 2008). These rocks consist of hard, jointed, basaltic and trachytic lava flows from the late Tertiary (Miocene) age, and are approximately 10-12 million years old (Forsyth et al. 2008). Flows are intersected by dykes, and are interbedded with breccias (scoria), agglomerate (course angular gravel), compacted sandy tuff (ash) and ancient buried soils (Massey et al. 2012a).

Overlying the volcanic rock is loess, comprised of windblown silt, greater than 1m in depth (Brown and Weeber 1992; Macfarlane and Yetton 2013). Loess is thickest on the base of slopes and in valleys due to re-deposition from higher slopes (Brown and Weeber 1992). Near-vertical coastal cliffs are located around Lyttelton Harbour and the outer coast and then continue inland to the eastern suburbs of Sumner and Redcliffs. In the suburban areas of Redcliffs and Sumner, the cliffs are no longer affected by wave action (Macfarlane and Yetton 2013). Sea cliffs are typically 15 to 30m high, and are steep, (between 65-85°) which makes the cliffs susceptible to collapse. Evidence of this is found from the existence of a talus apron at the base of many of these cliffs (Massey et al. 2012b).

Isolated rock falls and boulder roll from outcrops of volcanic rock have occurred along the valley sides, and at the foot of the cliffs and quarry walls in various locations throughout the Port Hills (Brown and Weeber 1992). Tunnel gullying, surface erosion, soil creep and mass movements are widespread throughout the Port Hills within the loess and loess-colluvium (Brown and Weeber 1992). Slope failure is particularly common during or after periods of heavy rain which can cause in loss of cohesive strength in loess and results in small period movements or creep movements (Brown and Weeber 1992).

1.4.2 Earthquake-induced Landsliding initiated by the 2010-2011 Canterbury Earthquake Sequence.

The impacts of the four main earthquakes in the Canterbury Earthquake Sequence are summarised in Table 1.2.

Table 1.2: Impacts of earthquakes in the Canterbury Earthquake Sequence (Modified from Berryman, 2012)

Earthquake	Impacts in Christchurch flat lands	Impacts in Port Hills
4^{th} September 2010	Damage to brick and Unreinforced Masonry buildings (URM) Widespread liquefaction and lateral Spreading in eastern Suburbs	Minor localised rockfall, and minor slump failures in loess Areas such as Sumner Road, Castle Hill, Dyers Pass Road, and Summit Road were affected by rock fall.
22^{nd} February 2011	Pre-1970 buildings and several modern building damaged Significant liquefaction in eastern suburbs	Extensive and widespread rockfall, Cliff Collapse and loess failure. Damage to infrastructure, dwellings, and structures, plus caused loss of life
13^{th} June 2011	Further damage to buildings affected in 22^{nd} February earthquake Further liquefaction in eastern suburbs	Rockfall and cliff collapse, extensive in eastern Port Hills, further damage to dwellings and infrastructure
23^{rd} December 2011	Minor building damage Minor damage in eastern suburbs	Minor cliff collapse and rockfall in port hills

Impact on the Port Hills was minor following the initiating 4^{th} September 2010 earthquake, with the majority of slope failure consisting of localised rockfall. The 22^{nd} February and 13^{th} June 2011 earthquakes impacted the Port Hills significantly and induced widespread slope failure throughout the Port Hills. Slope failures initiated by the 22^{nd} February and 13^{th} June 2011 earthquakes were intially categorised into four types of geotechnical hazards (Dellow et al. 2011):

- Rockfall associated with long distance boulder roll,
- Rockfall associated with cliff collapse,
- Failure in loess or colluvium,
- Localised retaining wall and fill failure.

The combination of these failure mechanisms caused damage to infrastructure, dwellings and structures in the Port Hills. Slope failure initiated by the 22^{nd} February 2011 earthquake were widespread throughout an area approximately $65km^2$ in the Port hills (Figure 1.5) extending from Godley Head to the east, Governors Bay to the west, Lyttelton to the south and Mount Pleasant to the north (Hancox et al. 2011).

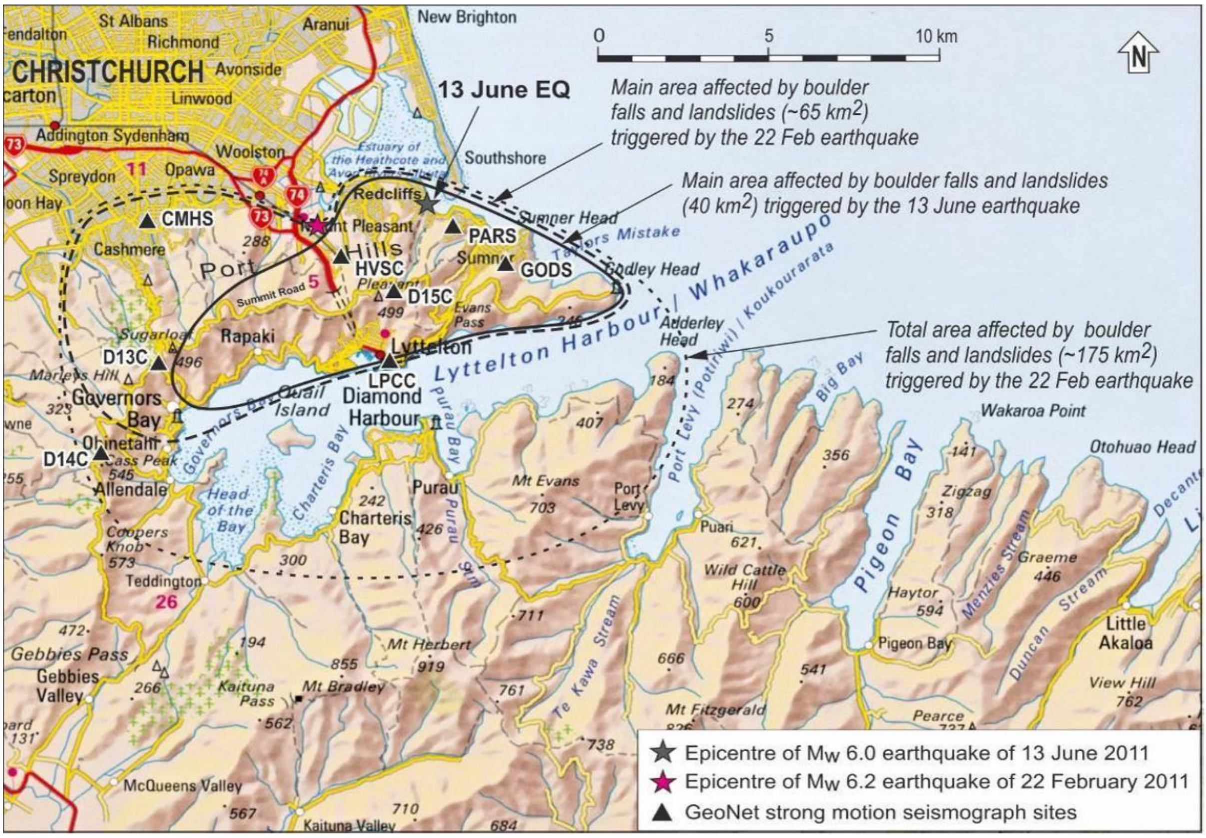


Figure 1.5: Location of area affected by earthquake-induced landsliding during the Canterbury Earthquake Sequence (Massey et al. (2012a), after Hancox et al., (2011))

1.4.2.1 Rockfall – Boulder Roll

Typically rockfall was released from joint controlled lava blocks from outcrops on valley walls (Figure 1.6). Sizes of the rocks which were released ranged from $0.1m^3$ to $10m^3$ depending on the spacing of jointing in the rock mass. Where joint spacing was greater than 1m rocks appeared to be more rounded (Dellow et al. 2011). Rockfall or boulder roll was one of the highest risk slope failure initiated by the earthquakes due to the velocity at which boulders and rocks generally progressed down slope, and in an unpredictable path. Further description of the classification and characteristics of rockfall is provided in Appendix A.

Figure 1.6: Illustration of the difference between Loess failure, Rockfall and Cliff Collapse. Photographs taken by M Villeneuve (left and top right); and GNS (bottom right).

1.4.2.2 Rockfall – Cliff Collapse

The mechanism of Cliff collapse has been defined as including the following terms: "cliff top recession" which describes the result of material releasing from the top and face of cliffs; and "debris avalanche" which describes the process of inundation of the toe of the slope (Massey et al. 2012b). In the Port Hills, cliff collapse typically occurred on steep present-day and former (Holocene) sea cliffs, former quarry faces and steep inland bluffs (Figure 1.6); (Dellow et al. 2011).

1.4.2.3 Loess failures

Failure characteristics that have been observed in loess include zones of compression (ground bulging), spring formation, and tensile cracking (Figure 1.6). Several interpretations of the mechanisms of failure in loess have been developed since the Canterbury Earthquake Sequence. Current interpretations of earthquake-induced failure in loess include:

- Mass movement in either loess or colluvium alone, or in a combination of rock, loess and colluvium. Failure mechanisms include slump, slide, fall, flow or avalanche, or a combination (Massey et al. 2013),
- Tensile fissures in loess which have been caused by a combination of bedrock fracturing, lateral spreading, and the ‘trampoline affect’ (Stephen-Brownie 2012). The trampoline affect describes a phenomenon observed in Christchurch by GNS Science where significant vertical ground accelerations experience during an earthquake result in weaker upper sedimentary layers to further upward than lower layers, this causes the separation of and collision of layers (Stephen-Brownie 2012).

Research into the failure mechanisms in loess and colluvium is ongoing, and as such there is currently no consistently used nomenclature for these failures. For this thesis slope failures in loess will be referred to as “loess failures”.

1.4.2.4 Retaining Wall Failure and Fill Failure

Retaining wall and fill failure did not present as great a life-safety risk immediately after the earthquake as the remaining three hazards because they were localised failures, and influenced smaller areas. Fill and retaining wall failure were typically <100m^3 and ranged from incipient cracking exhibiting an aperture of several millimetres, to extensive deformation (Dellow et al. 2011). As such, the overview of the geotechnical response to the Canterbury Earthquake Sequence developed in this thesis has had less emphasis the response to retaining wall failure in comparison to rockfall, cliff collapse and loess failures.

1.5 Review of earthquake-induced landslide hazard and risk

This section introduces a review of landslide hazard impacts and landslide risk management. Fundamental terminology of landslide hazard and risk used in this thesis has been provided to establish continuity in the use of risk assessment terms. Finally, a detailed overview of landslide risk management processes has been provided to contextualise the use of landslide hazard classification (presented in Appendix A) and analysis of consequence into a hazard management structure.

1.5.1 Landslide hazard impact

Internationally, landslide hazards have caused significant loss of life, damage and destruction to infrastructure and property (direct impacts), and economic loss (indirect impacts). Table 1.3 details the direct impacts from landslide movements which are related to the processes of inundation of material and slope deformation. Indirect impacts can include the interaction of landslide processes with environmental processes. One example of this is the formation of a landslide dam from the process of the inundation of landslide material into a river which can cause extensive loss of life, damage and destruction both upstream or downstream upon dam-break and inundation of water (Korup 2002). Indirect impacts can also include permanent restrictions to land use in zones of unstable geological features such as volcanoes.

Table 1.3: Direct impacts from landslides

Process	Direct Impacts
Inundation of material	• Damage to lifelines and structures from collision impact, collapse or damage by crushing from burial, associated air blast and distortion by gradual air pressure (Glade and Crozier 2004). • Loss of life or injury from impact, crushing or asphyxiation (Glade and Crozier 2004).
Slope Deformation	• Infrastructure and dwellings built at the top of a slope can undergo structural collapse, deformation or displacement from the removal of foundation support (Glade and Crozier 2004). • Deformation to lifelines, structures, and infrastructure from compression features at toe of slope and tension cracking which can induce strain on overlying structures causing damage (Dellow et al. 2011)

The severity of impact from a landslide depend the following characteristics (Crozier and Glade 2004; Hincks et al. 2013):

- The landslide type and magnitude.
  'Magnitude' refers to the volume of displaced mass and the areal extent of the slope failure feature, and the probable area of impact upon complete failure (Hincks et al. 2013).
- Run out characteristics:
  - Rate of failure/velocity of movement,
  - Travel distance,
  - Volume of debris;
- Exposure of elements at risk in the area of impact.
  'Exposure' is defined as the length or proportion of time that a person, building or other entity runs a risk (Alexander 2002).
  'Elements at risk' is defined as the people, buildings and structures, infrastructures, economic activities, public services, or any other defined values exposed to hazards in a given area (Glade et al. 2004).

The velocity of a landslide has significant influence on the impact. Rapidly moving landslides are considered the most hazardous as they travel at high velocities and can travel several kilometres beyond the slope in which they have initiated from (Keefer 1984; Glade and Crozier 2004). The large run out length results in a greater area affected by the landslide. Keefer (1984) proposed that >90% of deaths recorded from earthquake-induced landslides were attributed to rapid soil flows, rock avalanches and rockfalls which are fast moving. Unless the occurrence of a fast moving landslide can be anticipated, the onset of such slope failures are typically too rapid to allow evacuation or warning, consequently there can be potential for large numbers of fatalities (Hincks et al. 2013).

Table 1.4 presents a correlation between landslide velocity class (see Appendix A, Table A.7.2) and probable destruction significance as proposed by Cruden and Varnes (1996). The correlation has been developed based on several case histories in which landslide velocity and impact has been recorded. This information presents a relationship between increases in velocity with increase in recorded damage from impact (Cruden and Varnes 1996). Typically the major factors controlling the speed of movement include the size of the mass in motion, the slope angle, moisture content of in transported material, vegetation cover, slope angle, and horizontal and vertical travel distances (Glade and Crozier 2004). These characteristics can also affect the run out distance of a landslide (Glade and Crozier 2004; Hincks et al. 2013).

Table 1.4: Definition of Probable Destructive Significance of Landslides based on Velocity Classes according to Cruden and Varnes (1996)

Landslide Velocity Class	Probable destructive significance
7	Disaster of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
6	Some lives lost; velocity too great to permit all persons to escape
5	Escape evacuation possible; structures, possessions and equipment destroyed
4	Some temporary and insensitive structures can be temporarily maintained
3	Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during particular acceleration phase
2	Some permanent structures undamaged by movement
1	Imperceptible without instruments, construction possible with precautions

1.5.2 Landslide hazard and risk management

Risk is defined as the product of two components (ISSMGE 2004):

- *Hazard:* the probability of a specific event occurring in a given timeframe
- *Consequence*: the outcome or result of a hazard being realised. Includes components such as the cost of damage and loss of life.

Assessment of risk associated with slope failures is often addressed through landslide risk management frameworks developed by authors such as Fell et al. (2005); Australian Geomechanics Society (AGS 2000); and Crozier and Glade (2004) which provide a method for assessing risk. Landslide risk assessment typically includes a hazard analysis component which describes the process of characterisation and identification of potential landslides and their occurrence, and consequence analysis which quantifies the consequences of slope failure (Fell et al. 2005). Appendix A further examines landslide hazard classification and characterisation principles. Depending on the available data, degree of site investigation and nature of the consequences, landslide risk assessment frameworks may differ (Düzgün and Lacasse 2005).

The landslide risk management approach presented in Figure 1.7 may not directly apply to post-earthquake assessment of slope failure due to the urgency of the immediate response which requires the rapid assessment of risk based on limited data. The requirements for post-earthquake risk assessment of coseismic landslides also include prioritisation of high risk areas, and the rapid implementation of evacuations to manage the associated risk. The landslide risk management framework by Fell et al. (2005) (Figure 1.7) can, however, provide a supporting methodology for the landslide risk assessment in a post-disaster context.

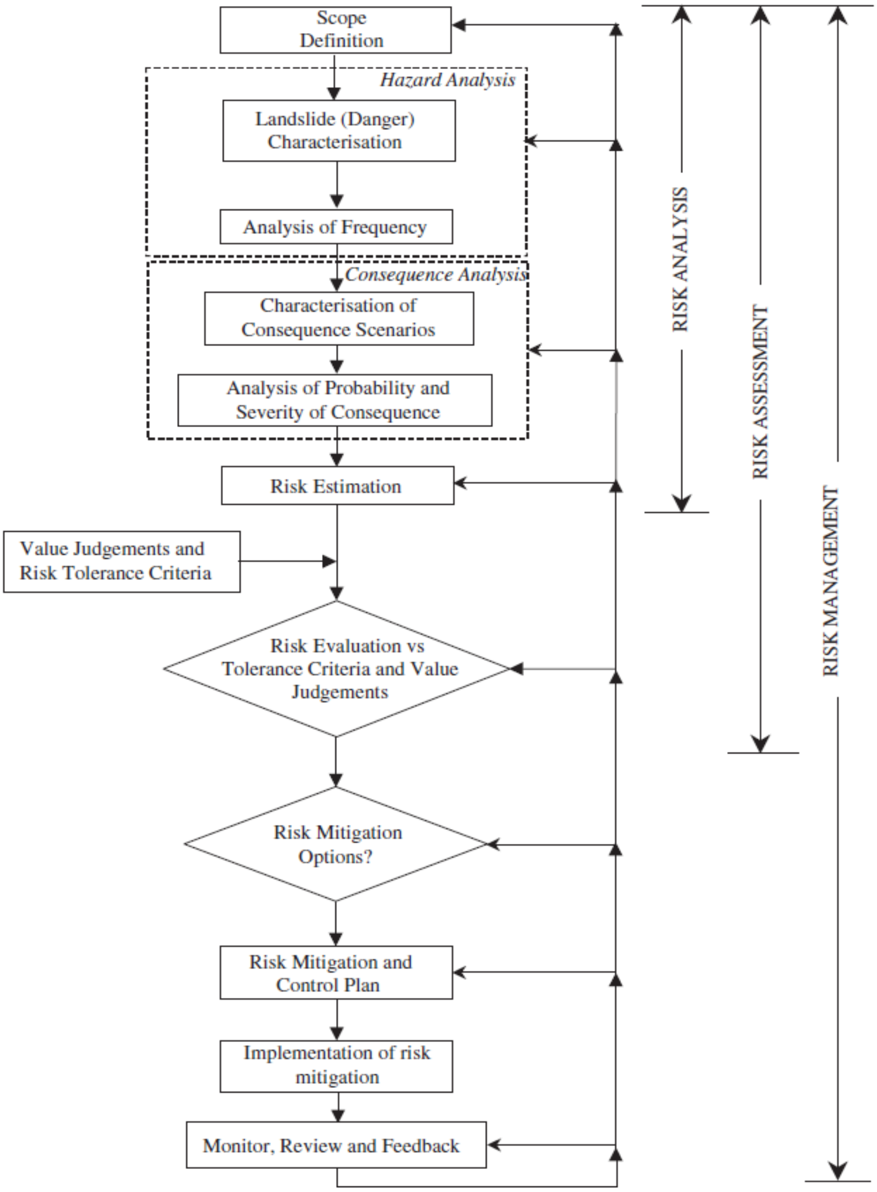


Figure 1.7: Landslide Risk Assessment and Management framework (Fell et al. 2005)

1.5.2.1 Scope

The first consideration in landslide risk assessment is the scope definition where the purpose of the study and the level of detail to be included in the assessment are defined (AGS 2007). Defining the scope ensures that the risk analysis addresses the relevant issues and concerns in regards to the analysis and often details the size of the area to be assessed, the geographic limits of the assessment, to what extent losses will be included in the analysis, the method of analysis, consideration of the consequences of the analysis and the involvement of external parties (Fell et al. 2005).

1.5.2.2 Hazard analysis

Landslide hazard analysis is divided into landslide characterisation and frequency analysis. The characterisation component of landslide hazard analysis should include the classification of the landslide type. Fell et al. (2005) suggests that landslide characterisation techniques outlined by Cruden and Varnes (1996) is a suitable system for hazard characterisation. Appendix A examines landslide hazard classification in accordance with Cruden and Varnes (1996) and presents research into characterisation of earthquake-induced landslides by Keefer (1984); Rodriguez et al. (1999); Keefer (2002).

The landslide hazard characterisation process includes an assessment of the physical extent of landsliding, the likely triggering events, potential pre-failure warning signs and the estimation of the anticipated travel distance, travel path, and velocity of movement (Picarelli et al. 2005). Investigation methods used to assess these characteristics often include remote sensing, landslide monitoring, field and laboratory based testing of slope materials, and geomorphological and geological mapping (Hincks et al. 2013).

Susceptibility mapping can also be used in regional hazard analysis to identify the areas where landsliding is likely to occur based on the state and properties of the slope (Crozier and Glade 2004; Hincks et al. 2013). Information that can be used in the analysis includes slope inclination, material constituents, vegetation cover, lithology and discontinuities in bedrock (Parise and Jibson 2000; Wills et al. 2011; Hincks et al. 2013). Susceptibility maps can inform emergency management, and pre-earthquake or post-earthquake site selection for construction and planning (Wills et al. 2011).

Numerical modelling and probabilistic modelling can also contribute to landslide hazard analysis for site specific slope assessments (Düzgün and Lacasse 2005). Typically the characterisation process of landslide features is followed by an analysis of the frequency of the landslide occurring. This can be calculated using a variety of methods including examination of historical data, use of geomorphological evidence, relationship between triggering event and landslide occurrence, and probabilistic modelling (Fell et al. 2005; Picarelli et al. 2005; AGS 2007).

1.5.2.3 Consequence analysis

The final component of landslide risk analysis included the assessment of the elements at risk, often called the consequence analysis. Comprehensive risk analysis typically includes physical consequences such as loss of life or damage to structures, but also societal and environmental consequences. Typically consequence analysis will involve the identification of the elements at risk, and the assessment of the temporal spatial probabilities for the elements at risk, and an assessment of the vulnerability of the elements at risk (Fell et al. 2005; AGS 2007). Vulnerability is defined as the expected degree of loss to a given element or se of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude (Glade et al. 2004).

1.5.2.4 Risk estimation and risk assessment

Combined, the hazard analysis and consequence analysis inform an estimation of the risk (Figure 1.7). Risk assessment refers to the comparison between the risk estimation against risk tolerance criteria or acceptability criteria (Düzgün and Lacasse 2005; Fell et al. 2005). The risk assessment process then informs the risk management process where landslide mitigation is planned and implemented.

1.5.2.5 Risk management

Hazard characterisation and consequence analysis contribute to an assessment of landslide risk. From an understanding of the risk an appropriate methodology to manage the hazard and risk can be proposed. Typical strategies for landslide risk management include:

1. **Risk Avoidance**
   Definition: An informed decision not to become involved in a risk situation (AGS 2000)
   Application: Includes land use restrictions and access restrictions (Schuster and Kockelman 1996; Hincks et al. 2013), relocation of infrastructure and inhabited areas

(Bromhead 2004). In a post-earthquake landslide risk management context, risk avoidance is utilised through the enforcement of evacuation based on initial geotechnical appraisal of the situation and the post event slope stability (Crozier 2004).

2. **Risk Reduction**

   Definition: A selective application of appropriate techniques and management principles to reduce either likelihood of an occurrence or its consequences, or both (AGS 2000)

   Application: Includes installation of engineering protection structures and early warning systems (Schuster and Kockelman 1996; Bromhead 2004; Hincks et al. 2013). Post-earthquake risk reduction may include emergency treatment of landslide source areas, and the installation of temporary stabilisation or protection structures.

3. **Risk Transfer**

   Definition: Shifting the responsibility or burden for loss to another party through legislation, contract, or other means. Risk transfer can also refer to shifting a physical risk or part thereof elsewhere (AGS 2000).

   Application: Distribute the burden of loss through legislation or insurance (Schuster and Kockelman 1996; Hincks et al. 2013).

An assessment of landslide hazard and risk is used to inform the suitability and effectiveness of each of these risk management options (Hincks et al. 2013). Hazard characterisation is used to anticipate the likely impacts of a landslide to the elements at risk and consequently informs decisions around the management of landslide impact (Crozier and Glade 2004). Landslide management techniques are influenced by landslide characteristics such as the velocity of failure (Figure 1.8). Literature indicates that for landslides up to Velocity Class 3 it may be possible to reduce the risk with the use of engineering works, however for faster movements (up to Velocity Class 5) forecasting is the primary tool for risk reduction (Hincks et al. 2013).

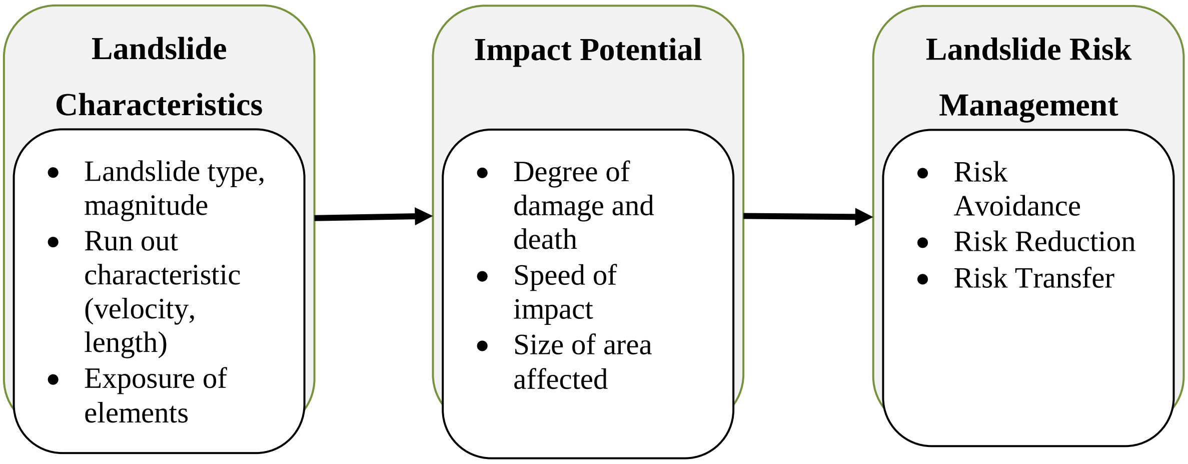


Figure 1.8: Relationship between landslide characterisation and landslide risk management

In a post-earthquake context, the movement velocity will affect the rapid risk management approach. For landslides in Velocity Classes 6 and 7, evacuation may not be possible due to the lack of time available to enforce the movement of people (Cruden and Varnes 1996) For landslides in Velocity Classes 4 and 5 evacuation is a probable and achievable form of response (Hincks et al. 2013). Characteristics such as the run out length will also affect the size of the impact area which may affect the degree of emergency evacuation required.

Landslides with velocity lower than this may not require evacuation, and risk reduction may be achieved through maintenance and stabilisation (Hincks et al. 2013). The management of risk associated with landslides is also dependant on the type of landslide and the amount of displacement that occurs. Slower moving, deep seated landslides can cause damage from earth pressures and differential shearing rather than collision or inundation of material (Glade and Crozier 2004). This may mean that the area is still habitable, however, engineering countermeasures may be required to manage the impact and desensitise structures from slope deformation (Bromhead 2004). The depth of movement will also affect the type of remedial measures that will be successful at a specific site (Glade and Crozier 2004).

1.6 Thesis Format

The thesis has been structured into the chapters summarised in Table 1.5 to provide coherent representation of the conducted research.

Table 1.5: Thesis chapter summary

Chapter	Title	Objectives(s)
1	Introduction	Presents the project background; thesis objectives and methodology; overview of the Canterbury Earthquake Sequence (geological context, seismological context and landslide hazards); and fundamentals of earthquake-induced landslide hazard and risk.
2	Research methodology	Outline method used to conduct research, including detail on data collection and analysis
3	Geotechnical response to slope failures prior to and during the Canterbury Earthquake Sequence	Provide an overview of the approach to landslide risk management in the Port Hills, Christchurch prior to the Canterbury Earthquake Sequence. Achieved through literature review and interviews with geotechnical professionals with current and former involvement in landslide risk management in the Port Hills. Documentation of the emergency response to earthquake-induced landsliding throughout the Canterbury Earthquake Sequence. Achieved through literature review and interviews with geotechnical professionals and emergency management personnel involved in the response.
4	Historical and international earthquake case studies	Documentation of the emergency response and recovery to historical international earthquakes which produced significant coseismic landslides. Review of earthquake response was achieved through review of literature. Case study earthquakes included: 1994 Northridge, California earthquake 1999 Chi-Chi, Taiwan earthquake 2008 Wenchuan, Sichuan, China earthquake
5	Analysis of the geotechnical response following large earthquakes – comparison between the Canterbury Earthquake Sequence and international examples	Present the primary requirements for post-earthquake risk assessment and management of earthquake-induced landsliding during emergency response based on case study analysis of the Canterbury Earthquake Sequence, with comparison to historical earthquake case studies reviewed in Chapter Four

Chapter	Title	Objectives(s)
6	Future geotechnical response to earthquake-induced landslides	Provide discussion around the requirements for geotechnical response to inform planning for future post-earthquake risk assessment and management of slope failures.
7	Summary, conclusion and recommendations	Presentation of a concise summary outlining the main thesis findings, conclusions and future work recommendations.

1.7 Summary

The Canterbury Earthquake Sequence provides an opportunity for comprehensive analysis of geotechnical response to coseismic slope failure hazards. Peak ground accelerations experienced during the CES, particularly after the 22nd February 2011 earthquake, exceeded design standard and previously recorded ground motions in New Zealand. The significant ground damage which occurred in the Port Hills during the 22nd February, 13th June and 23rd December 2011 earthquakes has been attributed to high ground accelerations and topographic amplification.

A review of landslide risk management adopted by Fell et al. (2005) and AGS (2000) has been conducted to provide grounding in conventional procedures for risk management of slope failures. To determine the applicability of this risk management procedure to post-earthquake response, the requirements and priorities of emergency response to earthquake-induced landslides must first be understood. This includes understanding the strategic requirements for implementation and coordination of post-earthquake landslide response. Hence this thesis.

Chapter Two: Research methodology

2.1 Introduction

The aim of this chapter is to outline the research methodology that has been conducted to inform a comprehensive case study analysis of the Canterbury Earthquake Sequence (CES). The aim of this research is to critically analyse the response by geotechnical professionals and local government to life safety risk posed by earthquake-induced landsliding during the CES. The intention of this research is to develop a discussion document which informs guidelines for post-earthquake geotechnical response to coseismic landslides. Because of the high seismic hazard in New Zealand (Stirling et al. 2002) it is important that lessons learnt from the CES are captured and used to prepare for future seismic events.

A mixed method approach has been employed with four principal phases:

1. A comprehensive literature review of the response to coseismic landslides during the following historical international earthquakes:
    i. 1994 Northridge California earthquake,
    ii. 1999 Chi-Chi, Taiwan earthquake,
    iii. 2008 Wenchuan, Sichuan, China earthquake
2. Interviewed individuals involved in the geotechnical response to the Canterbury Earthquake Sequence (CES) to inform a detailed case study analysis of post-earthquake response to earthquake-induced landslides
3. Interviews with analysis was undertaken to identify recurring themes and significant events during the CES. Data analysis was undertaken using NVivo software and sought to thoroughly examine information given by participants in the interviews and identify key components of the geotechnical risk assessment during the Christchurch earthquake sequence.
4. Comparison between historical international interviews and response to the CES to inform discussion concerning future response to earthquake-induced landslides and provide recommendations for guidelines for geotechnical response.

This chapter is supported by technical paper which details the methodology for this research (Appendix B).

2.2 Geotechnical precedent from historical international earthquakes

Prior to commencing interviews, a comprehensive literature review of immediate response to earthquake-induced landslides was conducted for the 1994 Northridge, California earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 2008 Wenchuan, China earthquake. The immediate response includes the post-earthquake emergency management of earthquake-induced landslides commencing hours to days after an earthquake until transition to recovery occurs several months later. The purpose of the detailed literature review (Chapter Five) is to examine the earthquake impacts and subsequent geotechnical response to earthquake-induced landslides to enable comparisons with the Canterbury Earthquake Sequence (CES), and to propose improved geotechnical response mechanisms.

The literature review has also informed the development of interview questions for conducting research into the CES. Table 2.1 provides comparison of the types of landslides induced by each of the three historical earthquake and the 22nd February 2011 earthquake during the CES. Boxes marked in Table 2.1 indicate the types of slope failure mechanisms that were observed post-earthquake in accordance with landslide classification outlined by Cruden and Varnes (1996).

Table 2.1: Comparison of slope failure mechanisms between historical earthquakes and Canterbury Earthquake Sequence

Slope failure mechanism	Northridge, California, USA	Chi-Chi, Taiwan	Wenchuan, Sichuan, China	CES, New Zealand
Falls	X	X	X	X
Slides	X	X	X	X
Flow/avalanche		X	X	X
Landslide Dam		X	X	

Reviewed literature for the Northridge, Wenchuan and Chi-Chi earthquakes provided information for the following research questions:

- Was an emergency geotechnical response plan prepared prior to the three international earthquakes examined in the literature?
- What were the critical tasks and priorities during the geotechnical response after the Northridge, Chi-Chi and Wenchuan earthquakes, and how did they progress?

- What were the similarities or differences in the geotechnical response and emergency management between the Northridge, Chi-Chi and Wenchuan earthquakes?
- Which organisations were involved in the geotechnical response? Which organisations were governing the response? Was there transparent integration and early communication between organisations involved in the response?

2.3 Canterbury Earthquake Sequence interviews

2.3.1 Interview participants

The contribution of local and national governmental agencies, as well as many private organisations and institutions, formed the geotechnical response to earthquake-induced slope failure in the Port Hills. Interview participants from these organisations were selected for this research based on their involvement in the emergency response in the Port Hills. A list of the primary organisations involved in either strategic level or tactical level is provided below. Strategic level involvement refers to individuals representing organisations involved in the management of the emergency response. Tactical level involvement includes participants who were involved in conducting field work and slope assessments on the Port Hills. Dividing organisations into strategic level and tactical levels allows an appreciation of components of practical response tasks to be gained while also encompassing the coordination and systems managing the response. Organisations and agencies listed below have been selected because of their level of involvement within the geotechnical response which was informed through recommendations from geotechnical engineers and engineering geologists involved in the CES response.

Strategic Level organisations:

- Christchurch City Council (CCC)
- Canterbury Regional Civil Defence

Tactical Level organisations:

- Urban Search and Rescue (USAR)
- Geotechnical consultancies involved in Port Hills Geotechnical Group (PHGG)
- University of Canterbury

Urban Search and Rescue (USAR) contributed to the coordination of geotechnical response while also conducting onsite field assessments of slope failures induced by the earthquake sequence. Despite this, USAR has been categorised as a tactical level organisation as their primary involvement was in field assessments at a tactical level. Representatives were not sought from organisations such as the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) or local CDEM because participants from other organisations who had similar involvement were interviewed to provide a representative sample.

2.3.2 Interview questions

Interviews were conducted in a semi-structured format which involved developing questions guided by the research objectives. The semi-structured method differs from a structured interview by allowing the interviewer to modify the pace and order of questions, or add further questions to as the interview progresses to probe further response from participants (Gillham 2000; Qu and Dumay 2011). The semi-structured interview method was selected for this research on the basis that it is the most commonly used qualitative research method because it allows for flexibility within the interview and enables the interviewer to probe for further information relative to the research (Qu and Dumay 2011). In accordance with the semi-structured methodology, a primary question set was developed for strategic level and tactical level participants, which aimed to address the following objectives:

- Establish the participant's role in the geotechnical response to the CES and how this changed temporally.
- Examine the priorities and requirements of geotechnical response to earthquake-induced landsliding during the CES and how they changed temporally.
- Identify significant events during the CES which influence the participant's involvement in the geotechnical response to coseismic slope failures.
- Ascertain what lessons the participant had learnt from their involvement in the geotechnical response during the CES.

The primary question set provided a 'check list' to ensure information relevant to the research was addressed. The combination of these questions primarily sought to examine the participant's temporal and spatial involvement after each major earthquake during the CES and identify lessons learnt during their involvement. This informed comparison between the response requirements of each earthquake, and allow deficiencies or developments to be highlighted. Questions regarding landslide risk management in the Port Hills prior to the CES were included to enable comparison between the perception of landslide risk and conducted landslide risk management techniques prior to and during the CES.

The primary question set is attached in Appendix D and was developed around the following sub-headings:

1. Previous disaster response experience,
2. Involvement in landslide risk assessment, and risk management prior to the CES,
3. Timeframe of participant's involvement in the response to the CES,
4. Spatial location of involvement in the Port Hills during the CES,
5. Role in the geotechnical response to the CES,
6. Organisation and agencies associated with during the response to the CES,
7. Current role in landslide risk management in the Port Hills,
8. Lessons learnt during the geotechnical response.

A second, individually tailored list of questions was developed for each participant to target specific details regarding the participant's or organisation's role during the response. The secondary question set was important for gaining details about role development and identifying issues specific to the participant. Both of the strategic and tactical level primary question sets are attached in Appendix D as part of the University of Canterbury ethics application for this research.

With the permission of the participant, interviews were recorded on a digital recorder and stored on password protected external hard drive and backed up on the University of Canterbury Geological Sciences network server which is both password protected and encrypted. Access to interview records was maintained restricted to the researcher and supervisors. Physical notes, tapes and the external hard drive were kept in a locked drawer inside a locked office in the Geological Sciences Department in the University of Canterbury. The identification and contact details of participants were maintained confidential throughout the research project.

2.3.3 Visual stimuli

Visual stimuli were presented during interviews to assist the participant's recollection of their role during the Christchurch Earthquake sequence (CES). The use of graphic elicitation is a valuable component of qualitative research which can include the use of maps, drawings, and photographs to improve communication between the researcher and the interview participant and yield contributions from participants which are difficult to achieve through verbal exchanges (Crilly et al. 2006). Table 2.2 outlines the visual stimuli used during interviews, and provides a description and justification of each document. Upon completion of an interview, visual documentation became included in the research as physical notes from the interview. An example of each document has been provided in Appendix C.

Table 2.2: Justification and description of visual documents

Interview material	Description and justification
Visual Timeline	A series of visual timelines were developed to provide temporal information of events that had occurred during the CES from September 2010 to September 2012 (Attached in Appendix C). These events included: • Local or National government level decisions such the declaration of a state of emergency or introduction of legislation during the CES • Large rainfall and snowfall events - rainfall data was collected from the NIWA website. Information from media releases and publically accessible reports. Timelines were also developed for two week, and ten day periods commencing after the February 2011 earthquake for participants who were active for a limited timeframe immediately after the earthquake. This allows more detail to be focussed on these time periods. Visual timelines aimed to provide a reference to prompt memories during the CES and guide discussion.
Topographic map	The map centred on Lyttelton and extended up to the estuary north of the Port Hills, and Westmorland to the west (attached in Appendix C). The purpose of the map was primarily to provide a visual aide where participants can spatially define the location of their involvement.

2.3.4 Ethical approval

Before research commenced an application to the University of Canterbury Human Ethics Committee was submitted to ensure that the research methods were conducted in accordance with the requirements of the committee. The application included research aims, methodology and outlined techniques to ensure the risk to participants involved in the research was minimised. This included addressing issues such as maintaining confidentiality of research data and participant's involvement, and detailing data usage and storage. The application to the University of Canterbury Human Ethics Committee is included in Appendix D.

An information sheet and consent form was generated to inform participants of the research aims and objectives, and outline arrangements for maintaining confidentiality. This ensured that the interviews were conducted in accordance with common practice for interviews in qualitative research, where interview participants are required to be informed of the interview process, the role of the researcher and how the interview data would be used before commencing the interview (Qu and Dumay 2011). The information sheet and consent form was approved as part of the ethics application processes and was distributed to participants prior to interviewing. The consent form was required to be signed by the interviewer and the participant before commencing the interview to provide evidence that the participant understood and agreed to the requirements for involvement in the research.

2.3.5 Data collection

2.3.5.1 Contacting participants

Initially participants were contacted via email to inform them of the aims for the research and invite their voluntary involvement. Upon agreeing, participants were provided an information sheet to provide further detail on the research and ethical considerations in regards to confidentiality of information upon participation. A copy of the consent form was also provided so that participants were aware of the participation requirements prior to meeting for the interview.

2.3.5.2 Interview location

The location of each interview was selected by the participant. The location was left to the participant to decide because it was important that the participant felt comfortable in the situation that they were being interviewed. Some participants were not in the country at the time of the interview process and so were interviewed via Skype or email. All verbal interviews were audio recorded to ensure that all information was captured.

2.4 Analysis of interview data

In order to examine the geotechnical response during the Christchurch Earthquake Sequence; several iterations of data analysis were conducted. These include:

1. Comprehensive transcription of interview dialogue,
2. Development of summaries of each interview for participant's review,
3. Analysis of interview dialogue using thematic coding in NVivo

2.4.1 Transcription

Comprehensive transcription of each interview dialogue commenced immediately after each interview. The majority of the transcription was conducted by Merrill Corporation NZ, located in Christchurch, however several of the interviews were transcribed by a self employed individual. Prior to transcription commencing, amendments were approved by the University of Canterbury Human Ethics Committee. For the self-employed individual, a confidentiality agreement was developed by the research to ensure privacy of interview dialogue (Appendix D). Files were stored on a password protected USB and participant's names were not disclosed to the transcriber.

Prior to Merrill Corporation NZ conducting transcription, an amendment was approved by the University of Canterbury Human Ethics Committee to ensure the confidentiality agreement between Merrill Corporation NZ and its employees would maintain the privacy of interview dialogue (Appendix D). Furthermore, participant's identification information was maintained confidential from Merrill Corporation NZ. Upon transcription, files were stored in a password protected online storage facility managed by Merrill Corporation NZ, accessible only to the researcher. Transcription of the interview dialogue enabled quotes to be extracted from interviews and timestamps to be positioned at the start of each paragraph to enable correlation between audio files and transcription. This facilitated the accessibility of portions of the dialogue.

2.4.2 Interview summaries

At the conclusion of the interview phase, the analysis phase commenced through preparation of interview summaries. Typically, the validity of qualitative research is dependent on the degree at which the researcher's interpretation corresponds to reality or the interview participant's presentation of reality (Cho and Trent 2006). Consequently interview summaries aimed to improve transparency and validity of the researcher's interpretation of interview dialogue. Interview summaries were compiled from listening to interview dialogue and identifying the recurring ideas or significant events within the discussion. The summaries were consolidated into a table which consisted of two columns. One column listed the salient themes and statements identified in the interview, while the adjoining column remained clear to provide participants the opportunity to agree with the statements or provide comments or amendments.

Interview summaries were divided into sub-headings to present the researcher's interpretation of the progression of the participant's role and involvement during the CES.

The following sub-headings were used in the interview summaries:

- Response post 4th September 2010 earthquake (if applicable)
- Response post 22nd February 2011 earthquake
- Response post 13th June 2011 earthquake
- General statements
- Lessons learnt

Summaries were distributed via email with a supporting outline of the aim of the interview summary. Participants were required to return a reviewed version of the interview summary within seven days unless further time was requested, at which time the data became part of the research. Interview summaries were an important part of the analysis procedure because it enabled clarification of ideas and statements, and gave opportunity for participants to respond and provide feedback regarding the researcher's interpretation of the data provided. This process sought to endorse the credibility of the researcher's interpretation of the data and acted as a form of quality control in the early stages of the data analysis (King and Horrocks 2010). Further clarification aimed to increase the consistency of information, decrease the risk of significant change in the data during the research period, and aimed to achieve transparency within the data analysis (King and Horrocks 2010).

2.4.3 Interview coding

Upon approval of interview summaries, dialogue analysis commenced using of the software programme NVivo. NVivo is a qualitative analysis software package produced by QSR International. The main function of the software is to act as a tool for the collection, organisation and analysis of data from mixed method research. For this research NVivo was used to analyse audio data and interview transcriptions. It was also used to store and analyse documents that had been provided by the participants during the interviews.

Audio files and transcriptions were uploaded to NVivo simultaneously so that the interview could be listened to in conjunction with transcription coding. Simultaneous analysis was important because emotion in the participant's voice could be used for identifying negative or positive attitudes to events or themes (Gillham 2000). Each audio file and the associated transcript were labelled within Nvivo using the participant's name and were distinguished based on their representing organisations using colour coding.

2.4.3.1 Setting up nodes

Prior to the coding, several Nodes were established to reflect the components of geotechnical response that were identified during review of historical international earthquakes. Nodes represent thematic categories identified by the researcher (Gillham 2000; King and Horrocks 2010). Once a section of the data is coded to a Node it becomes categorised with the theme that the node represents. Data was coded to multiple nodes depending on associations with multiple themes (Gillham 2000; King and Horrocks 2010). At the duration of the analysis, the researcher can examine a node and revise the data assigned or coded into that category.

Additional nodes were developed as coding of interviews progressed. Nodes were assigned a description when created to ensure that consistency was maintained within the coding analysis. Node descriptors ensured that upon disruption of coding the researcher could review what theme each node represents which increased the transferability of the coding process. Nodes were established for organisations or agencies involved so that the role of each organisation could be captured in the analysis. Nodes were also created for two interview questions which were specifically asked in each interview to provide an overview of the lessons learnt during the geotechnical response on the Port Hills. Specifically coded questions included:

1. What are the three most important lessons you have learnt from responding to the earthquake sequence?
2. Was it obvious which authorities were responsible for the response in the Port Hills immediately after the earthquake?

Responses to these particular questions were collated to form a list of opinions and interpretations of lessons learnt.

2.4.3.2 Coding interview dialogue

Interviews were coded in a hierarchical system, commencing with strategic level interviews, then tactical level interviews. This enabled an appreciation of the overarching coordination requirements before examining the tactical level tasks of the geotechnical response. Significant themes, challenges, and successes during the response to the CES were emphasised through recurring reference within participant's statements which accentuated their importance and significance to the geotechnical response (Gillham 2000; King and Horrocks 2010). Statements were identified from interview dialogue and were coded to a node or multiple nodes depending on the association with themes (Gillham 2000; King and Horrocks 2010). Statements included phrases, sentences or paragraphs. Single words were not coded due to lack of information and guidance regarding the context. Ensuring context was maintained became particularly important in the consolidation results from interview analysis. Analysis was conducted slowly and thoroughly in order to fully appreciate the combination of nodes (ideas) that each statement referenced. Consistency of interview coding and analysis was important and maintained through the use of node descriptions and ensuring that all available nodes were reviewed before finalising node selection for the selected text.

2.4.3.3 Final NVivo analysis – node organisation

At the conclusion of the analysis, nodes were revised to eliminate multiplication of themes. Generally coded statements and information was assigned to the appropriate node and as such division or merging of nodes was not required.

2.5 Interpretation of interview results

2.5.1 Results interpretation and development of recommendations

Interpretation of interview results was conducted in several iterations:

1. Results from interview analysis have been presented as a coherent timeline of the Canterbury Earthquake Sequence (CES) commencing 4th September 2010 until December 2011. The purpose of the CES geotechnical response timeline is to provide representation of the temporal evolution of the geotechnical response tasks, requirements and priorities. Recovery activities were also included to enable comparison between the emergency response and the subsequent recovery phase.
2. Significant themes were identified from coding analysis. Challenges and successes identified within each theme were examined to consider the probable causes which led to developments in the geotechnical response. The response to the CES was compared to the responses to historical international earthquakes to provide supporting evidence or contrast with comparable events.
3. A temporal model of the geotechnical response to the CES was developed to emphasis the evolution of tasks and requirements in the context of post-earthquake coordination of a geotechnical response and management coseismic landslide hazard. Phases within the model were developed to delineate stages within the geotechnical response are supported through comparison with historical international earthquakes.

The interpretation of interview results informed the final objective of this research which is to develop recommendations on the requirements for post-earthquake geotechnical response based on results from the case study analysis of the Canterbury Earthquake Sequence and comparison with literature review of the 1999 Chi-Chi Taiwan earthquake, the 1994 Northridge earthquake and the 2008 Wenchuan earthquake. Comparison across events ensured the credibility and transferability of recommendations to inform guideline development, and supports the applicability of recommendations internationally. Recommendations (Chapter Six) aimed to inform future response to earthquake-induced slope failure to achieve a coordinated and efficient response. Further detail of the methodology for development of recommendations for geotechnical guidelines can also be found in Appendix B.

2.5.2 Structure and use of recommendations

Recommendations (Chapter Six) were developed as a discussion document to illustrate methods for management and practice of post-earthquake geotechnical response to advise the geotechnical community and government level organisations of recommendations for the development of formalised geotechnical response guidelines. Chapter six aims to inform organisations such as Civil Defence and Emergency Management Groups (CDEM), national and local government, consultancies and research based contributors who were involved in the geotechnical response to the Canterbury Earthquake Sequence.

2.5.3 Limitations to research methodology

Although semi-structured interviews are used extensively in qualitative research, there are limitations to this research methodology (Qu and Dumay 2011). Limitations can include the following (Qu and Dumay 2011; Roulston 2013):

1. Participants/interviewees may have inaccurate recollections of their experiences.
2. Participants/interviewees may not articulate responses to questions clearly.
3. Participants/interviewees may experience difficulty in comprehending the interviewers' questions.
4. Expression of emotional states by participants may distort the information provided in response to questions.
5. Participants/interviewees may provide inconsistent or contradictory information.
6. Participants/interviewees may avoid questions or may be uncooperative.
7. Cultural differences between the interviewer and participant may mean that communication is hindered by differences in meanings of words and phrases.
8. The researcher may misinterpret the information that the participant discloses which raises concern regarding the validity of the research.

Interviews are considered “successful” when the participant provides an objective and factual report of their experiences regarding the event/s in questions (Roulston 2013). The limitations listed above can be minimise through the use of pre-planning prior to interviews commencing (Qu and Dumay 2011). For this research, several of these limitations such as inaccuracies in information collected during interviews were addressed through the use of interview summaries (section 2.4.2) which allowed participant to review the information. Furthermore, ongoing interaction with participants via email enabled further clarification of responses that were not well articulated in the interviews.

2.6 Summary

This research has been conducted using a mixed-method approach to inform a case study analysis of the Canterbury Earthquake Sequence (CES), and develop recommendations for future response to earthquake-induced slope failures. Case study analysis has been informed through interviews with personnel from a selection of organisations that were involved in the geotechnical response to earthquake-induced landslides during the CES. Interview analysis has been conducted using NVivo to identify critical themes, priorities and tasks during the response.

A literature review of international earthquake-induced landslide responses has been conducted to identify fundamental aspects of response to earthquake-induced landslides, and provide comparison between geotechnical response methodologies conducted in New Zealand and internationally. Interpretation of the case study analysis has informed the development of a discussion document (Chapter six) to provide recommendations for future geotechnical response to earthquake-induced slope failure.

Chapter Three: Geotechnical response to slope failures prior to and during the Canterbury Earthquake Sequence

3.1 Introduction

The Canterbury earthquake sequence (CES) presents a New Zealand case study for analysing response by local government and geotechnical professionals to widespread and complex earthquake-induced slope failure in an urban environment. This chapter establishes the context of landslide risk and landslide risk management in the Port Hills prior to the CES based on literature review and information collected during interviews. To examine the post-earthquake geotechnical response and management of earthquake-induced slope failure implemented during the CES, a timeline of the response has been developed from information collected from interviews and supporting literature. Significant themes identified during the geotechnical response to earthquake-induced slope failure have been identified to contextualise the response mechanisms which were initiated during the CES.

3.2 Geotechnical risk management in Port Hills prior to Canterbury Earthquake Sequence

To provide context to the response to earthquake-induced slope failure during the CES, it is important to examine the stability of the Port Hills prior to the earthquakes occurring, and understand the subsequent approach to management of risk from slope failure. These understandings contribute to the approach to landslide risk management in the Port Hills prior to the earthquake sequence.

3.2.1 Landslide hazard in the Port Hills

Prior to the earthquake sequence there have been a series of recorded slope failures which have occurred in the Port Hills (Table 3.1). Infrequently these events caused damage to structures and infrastructure. Primarily the more damaging slope failures, such as the 1907 and 1912 rockfall on Sumner Road, and the rockfall at Heberden Avenue and Wakefield

Avenue in 2000 and 2006 respectively appear to have been associated with the occurrence of rainfall (Star Newspaper 1907; Brown and Weeber 1992; Massey et al. 2012a). Anecdotal evidence and discussion from interviews suggests that minor rockfall and isolated boulder roll was the most common form of slope failure in the Port Hills. However many of these events have not been recorded. This is likely to have been because they were minor events which did not cause significant damage.

Table 3.1: Recorded Slope failures in the Port Hills prior to the Canterbury Earthquake Sequence

Year	Location	Type of failure and Volume of material	Impact	Reference
1907	Cliff at Sumner Road, Shag Rock Reserve (northern end of cliff) – Failure occurred after heavy rain	Failure mechanism not specified 3000-5000tons material (~1500-2000m^3)	Inundation of roadway, damage to infrastructure such as water mains and tramline	Star Newspaper 1907
1912	Cliff at Sumner Road, Shag Rock Reserve (southern end of cliff) – Failure associated with rainfall but did not occur during rainfall	Rockfall 150m^3	Inundation of roadway and tramline	Brown and Weeber 1992
1986	Scarbourgh	Isolated rockfall Volume not specified	Closed Edwin Mouldey Track Damaged Pump station	Elder et al. 1991; Brown and Weeber 1992
1986	Governors Bay	Isolated Boulder roll Volume not specified	Damage to rear wall of house	Elder et al. 1991
1992	Raekura Place, Red Cliffs	Rockfall ~50m^3	Minor damage to property	Bell 1992
1996-2011	Various locations in Port Hills	6 landslides (types not specified) Each failure <10m^3	Some affected roads	Massey et al. 2012 (GNS Landslide Database)
2000	Heberden Avenue Rainfall initiated	Rockfall (volume not specified)	House Destroyed	Massey et al. 2012 (GNS Landslide Database)
2006	Wakefield Avenue Rainfall initiated	Rockfall Several hundred cubic metres	Two homes damaged	Massey et al. 2012 (GNS Landslide Database)

From historical evidence of slope failure in the Port Hills under static conditions (Table 3.1) and geomorphological evidence it was expected that earthquake-induced landsliding in the

Port Hills was likely to include boulder roll, rock fall, rock slide and failure in loess (Elder et al. 1991). In a review of the Christchurch earthquake hazard by Elder et al. 1991 for the Earthquake Commission (EQC) it was identified that in the Port Hills there were many steep slopes with the potential to generate significant debris during an earthquake, however, the extent of susceptible slopes had not been quantified. This was supported by the Centre for Advanced Engineering (1997) (CAE), who identified a risk of slope failures impacting lifelines in the Port Hills in the event of a severe rainstorm (1 in 100-year local rainstorm) or a 1 in 100 or 150 year earthquake occurring in late winter where ground water levels are elevated. Elder et al. (1991) proposed that rock slopes in the Port Hills will fail more frequently than soil slopes, and are likely to undergo minor failure from shaking intensities between VI to VII, i.e. earthquake with 1 in 12 to 25 year return period. Thus identifying the potential for damage to residential areas where dwellings are adjacent to steep rock slopes (Elder et al. 1991).

Although earthquake-induced landsliding had been identified as a hazard in Christchurch the scale of slope failure experienced in the Christchurch Earthquake Sequence had never been previously observed in the Port Hills. Because of this, the extent of the slope failure experienced in the Christchurch Earthquake Sequence was not appreciated from a planning perspective. The mechanism of cliff collapse, which occurred after the 22nd February 2011 earthquake and includes the process of debris avalanche and cliff top recession, had not previously been considered prior to the Canterbury Earthquake Sequence.

3.2.2 Seismic hazard in Christchurch

Prior to the earthquake sequence, seismic hazard in Christchurch was primarily focussed on known distal active faults in the region such as the Alpine Fault, the Hope fault, Porters Pass Tectonic zone, Pegasus Bay fault, and Kaiwara Fault where earthquakes larger than magnitude 7 had previously been recorded (Sinclair 2008; Stirling et al. 2008). Figure 3.1 shows the active faults within a 200km radius of Christchurch City that scientists were aware of prior to the Canterbury earthquake sequence.

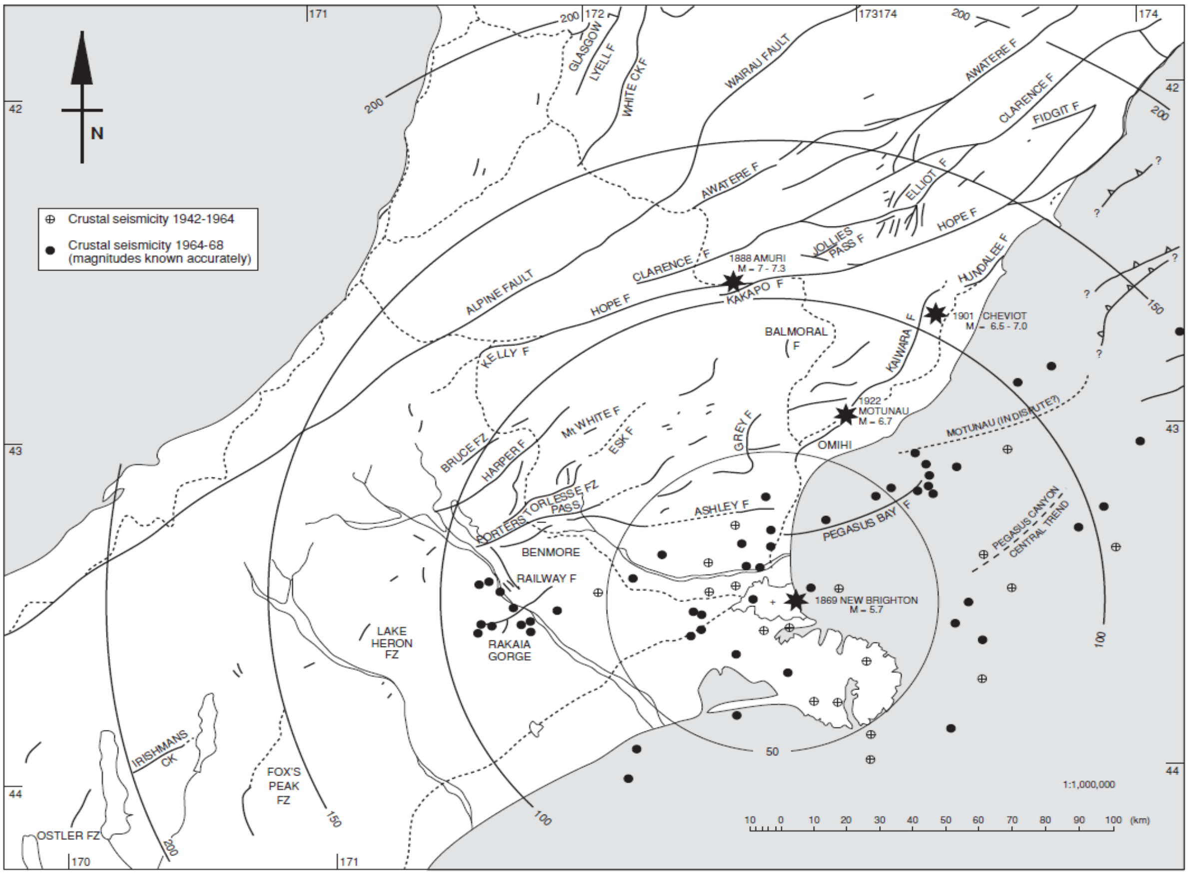


Figure 3.1: Known active faults within 200km of Christchurch prior to the Canterbury Earthquake Sequence (Centre for Advanced Engineering 1997)

Close proximity events were not included in the probabilistic seismic hazard model for the Canterbury region and which indicated a low probability of a local rupture event (Stirling et al. 2008). Estimated peak ground accelerations (PGA) for Christchurch were 0.31g and 0.4g for earthquakes with return periods of 500 and 1000 years respectively for class C (shallow soil) site conditions (Stirling et al. 2008). These estimated PGAs were significantly less than what was experienced in the Port Hills during the 22nd February and 23rd June 2011 earthquakes. Figure 3.2 presents the probabilistic seismic hazard maps for the Canterbury region based on the 2008 probabilistic seismic hazard model developed by Stirling et al. (2008).

Several historic earthquake events have been recorded which were located in close proximity (<20km) from Christchurch City, however no coseismic landslides in the Port Hills have been associated with these events. In 1869 a local source M_W 4.7-4.9 earthquake was recorded in Christchurch City and was described as the most damaging historical earthquake before the Christchurch Earthquake Sequence (Stirling et al. 1999; Downes and Yetton 2012). Damage to chimneys and brick and stone masonry buildings occurred in Christchurch suburbs and the central business district, however no liquefaction or ground damage was reported (Downes and Yetton 2012). The earthquake epicentre was first thought to have been located in New Brighton, however recent research suggests the earthquake was located within 5km of the Central Business District (Downes and Yetton 2012).

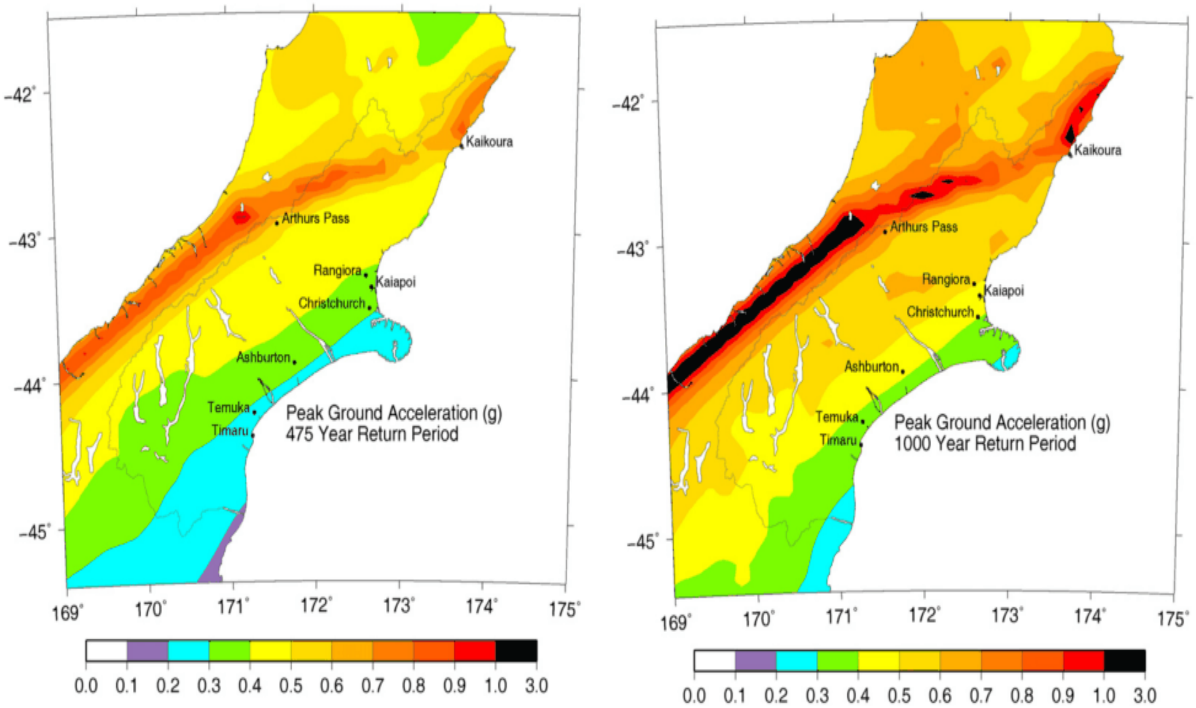


Figure 3.2: Probabilistic seismic hazard maps for the Canterbury region. Maps show the levels of peak ground acceleration (PGA) for return periods of 475 and 1000 years on class C (shallow soil) site conditions. Accelerations are presented in units of g.

In 1870 an earthquake ruptured near Lake Ellesmere, which caused MM6 intensity shaking in Christchurch using the Dowrick (1996) version of the Modified Mercalli Intensity Scale (Downes and Yetton 2012). These earthquakes, with the addition of other smaller earthquakes within a 50km radius of Christchurch City, indicated that close proximity faulting directly in the Christchurch City area was a possibility (Elder et al. 1991). However, a study completed for Canterbury Regional Council (now Environment Canterbury) concerning Earthquake Hazard and Risk Assessment noted the inadequacy of information regarding these historical close proximity earthquakes in Canterbury (Pettinga et al. 1998).

3.2.3 Landslide risk management in the Port Hills

In 1997 Environment Canterbury (Canterbury Regional Council) commissioned a series of studies to further the understanding of seismic hazard in the Canterbury region (Kingsbury et al. 2001). Under the requirements of the Resource Management Act (1991) (RMA) regional and local authorities are required to address the control land use for the mitigation or avoidance of the affects of natural hazards on the understanding that the impacts from natural hazards can be managed by hazard reduction, loss sharing and event modification (Hull 1997). Consequently restrictions in land use development have been previously enforced through the district plan for Christchurch City and surrounding local authorities such as Selwyn district and Waimakariri district.

Furthermore, with the knowledge that slope failures could pose a significant hazard in the event of a significant rainstorm or earthquake, analysis of aerial photographs and field observations informed the division of the Port Hills into slope hazard zones (Centre for Advanced Engineering 1997; Sinclair 2008). Pre-earthquake Port Hills slope hazard zones have been attached in Appendix E. Hazard zones broadly corresponded to the level of hazard, and advised on the requirement for site investigation prior to construction or future subdivisions (Centre for Advanced Engineering 1997). Due to the infrequency of large scale, damaging slope failures in the Port Hills, risk management was often primarily focussed on isolated boulder roll or rockfalls which were typically more common. To manage the risk of rockfall, mitigation techniques were recommended to specific sites where there was risk of impact to properties or lifelines.

"That was what we did, we built fences, we dug ditches, we built bunds, we scaled, we avoided in some cases but generally speaking we didn't avoid, because we weren't expecting blocks the size of this table to come down". – Senior Geotechnical Consultant

Mitigation techniques used for reducing the risk of rockfall to residents in the Port Hills included rock removal, stabilisation, and installation of engineered protection structures. Rock removal included the identification of loose or hazardous material on slopes and then removal of the material by scaling of the slope. Stabilisation or reinforcement of slopes included treatment of weakened material in some areas by use of rock bolting, shotcrete and installation of mesh on rock slopes.

3.3 Geotechnical response to earthquake-induced landslides during the Canterbury Earthquake Sequence.

3.3.1 4th September 2010 earthquake

Slope failure initiated in the Port Hills during the Canterbury Earthquake Sequence (CES) resulted in the involvement of the geotechnical community in the management of geotechnical hazard and risk. Involvement of the geotechnical community was progressive, with the least involvement required after the 4th September 2010 earthquake due to the relatively minor impact of the earthquake on the Port Hills.

After the 4th September 2010 earthquake the geotechnical response was managed through the involvement of local geotechnical professionals maintained on a contractual basis under the direction of Christchurch City Council (CCC). The response included the requirement to assess slopes to inform road use restrictions and road closures during the state of local emergency which commenced on the 4th September 2010 and ceased on the 16th September 2010. A state of local emergency was declared in Christchurch city, Selwyn district, and Waimakariri district.

After the state of emergency ceased, a local geotechnical professional was contracted by CCC to report on the impact of the earthquake on the Port Hills. The report was to be delivered to the CCC on the 22nd February 2011 but was never delivered due to the 22nd February 2011 earthquake which caused further damage to the city and the Port Hills.

3.3.2 22nd February and 13th June 2011 earthquakes

The most extensive involvement from the geotechnical community was required after the 22nd February 2011 earthquake, when widespread slope failure resulted in the development of a large geotechnical response contingent which later formed the Port Hills Geotechnical Group (PHGG). After the 22nd February 2011 earthquake, the geotechnical response involved rapid risk assessment of slope failures to inform the implementation of risk management techniques such as evacuations, road closures, and restrictions to building use. As such, protection of life safety was a priority for the response group in the aftermath of the earthquake. A state of national emergency was declared on the 23rd February 2011, and remained enforced until the 30th April 2011.

Coordination of the geotechnical response was also a priority after the 22nd February 2011 earthquake. During the initial 48 hours post-earthquake, geotechnical professionals mobilised individually and there was no management structure to coordinate the response. By the 24th February 2011 communication between geotechnical professionals increased through daily meetings, which highlighted the requirement for a coordination framework to be developed within the response. Developments in coordination were driven by the need to formulate a framework for efficient execution of life safety risk assessment so that the extent of slopes affected by the earthquake could be assessed as quickly and as thoroughly as possible.

Within one week of the earthquake a format for liaison between USAR and geotechnical professionals was established, and daily meetings were initiated by a leader within the geotechnical group to facilitate discussions around the coordination and execution of the response. Over the course of the week, a standard slope assessment format was developed and the Port Hills were divided into nine sectors that were assigned to geotechnical consultancies who were involved in the response. These developments formalised data collection and deployment processes and enabled a thorough execution of slope assessments by mitigating the duplication of slope assessments.

When the state of national emergency ceased further restructuring took place within the PHGG, and contractual agreements between geotechnical consultancies and the Christchurch City Council (CCC) were developed. The protection of life safety remained a priority for the Port Hills Geotechnical Group until 2013 when the group was disbanded. The PHGG response to slope failures after the 13th June 2011 earthquake continued in the same format that was in place at the end of the state of national emergency. Because further slope failure was initiated, reassessment of slopes in the Port Hills was required after the 13th June 2011 earthquake to inform further building use restriction.

From analysis of interview data collected during this research a timeline has been developed to present how the geotechnical response to earthquake-induced landsliding changed over time from the 4th September 2010 earthquake (Table 3.2, Table 3.3, and Table 3.4). For Table 3.3, colour coding has been used to relate activities to themes in the response, i.e. text in yellow relates to life safety, blue relates to coordination of the geotechnical response, and green relates to public communication. These timelines present the involvement of Civil

Defence and Emergency Management (CDEM), Christchurch City Council (CCC), Urban Search and Rescue (USAR) and geotechnical professionals (including GNS and local geotechnical professionals who weeks after the 22nd February 2011 earthquake formed the Port Hills Geotechnical Group). The involvement of each organisation was influenced by the changing priorities throughout the response, and the degree of formalised coordination and legislation.

Table 3.2: Port Hills geotechnical response timeline between September 2010 - April 2011

Year	Month	State	Civil Defence	Christchurch City Council (CCC)	Geotechnical Professionals	USAR
2010	September	State of Emergency	MM9 — 4th September - M_W 7.1 Earthquake caused few localised rockfalls and loess failures in the Port Hills			
			4th -16th Sept - State of Local Emergency Declared in Christchurch City, Selwyn District and Waimakariri District			
			Emergency Operations Centre (EoC) and Emergency Coordination Centre (ECC) established	Provide staff to civil defence during state of emergency Commission impact assessment for Port Hills	Impact assessment mobilised through previous engagement in Port Hills under CCC	No mobilisation of USAR geotechnical professionals to Port Hills
			14th Sept - Canterbury Earthquake Response and Recovery Act 2010 - Canterbury Earthquake Recovery Commission established			
			Recovery passes over to Canterbury Earthquake Response and Recovery Commission and local authorities	Rockfall information published on Christchurch City Council website Several roads closed or had restricted use after the earthquake; including Evans Pass Road and Sumner Road. Roads closed while hazard mitigation works and clearing were undertaken.	Assessment focussed on Lifelines and main arterial routes Recommendations for Road Closures, remedial works and clearing of debris	
	October				Development of impact assessment report Clearing of debris and remedial measures continue	
			15th October- Fletcher Construction appointed by EQC to run Canterbury earthquake project management office 21st October - Stage 1 EQC Geotechnical Report Released			
				Roads reopen – Sumner Road reopens end of October		
	November			8th November - Community Meetings for residents affected by land remediation (flat lands) commence	Development of impact assessment report continues	
	December		1st Dec - EQC Stage 2 Geotechnical Report Released	3rd,6th, 10th Dec - Earthquake recovery meetings – property and business owners	Development of impact assessment report continues	
			26th December - Boxing Day Earthquake			
2011	January				Development of impact assessment report	
	February - April	National State of Emergency	MM9 — 22nd February - Earthquake M_W 6.2 – caused widespread rockfall, cliff collapse and landslides in Port Hills			
			23rd Feb - National State of Emergency declared			
			See Table 3.3			

Table 3.3: Port Hills geotechnical response timeline between 22nd February - 30th April 2011

Response to earthquake-induced slope failures

	MM9 — February 22^{nd}- 23^{rd}	February 24^{th}- 28^{th}	March 1^{st} – 14^{th}	March 15^{th} – April 30^{th}
	1-2 days post-earthquake	3-7 days post-earthquake	1-2 weeks post-earthquake	1-2 months post-earthquake
Events	22^{nd} February - Earthquake M_W 6.2 – caused widespread rockfall, cliff collapse and landslides in Port Hills		Canterbury Earthquake Recovery Authority (CERA) set up under the State Sector Act 1988	16^{th} April - Earthquake - M_L 5.3 - Caused some localised rockfalls, and cliff collapse on Port Hills 30^{th} April - National State of Emergency Lifted. Recovery handed to CERA
USAR	• Hazard identification and rapid qualitative assessment of slope to inform evacuations and lifeline safety • Evacuations implemented immediately (some residents self evacuated) • Strategic routes between Lyttelton and Sumner, and Sumner and Christchurch City stayed a priority for USAR for approximately the first three weeks of the response. Sumner was particularly vulnerable due to the limited accessibility to the suburb and the requirement for water to reach the suburb • Body recovery commences • USAR personnel report daily to USAR base and CDEM • Initial deployment to lifeline routes, further deployment based on observations • USAR communicate individually with residents	• Hazard identification and rapid qualitative assessment of slope to inform evacuations and lifeline safety continues • Recovery of bodies continues • USAR communicated directly to EoC, Fire Brigade Command, local fire brigade and Police regarding evacuation requirements • Coordination with local geotechnical professionals increases - Geotechnical professionals provide recommendations to USAR and CDEM for evacuations • Daily report to USAR base and CDEM continues • USAR involvement with daily meetings of geotechnical response commences • USAR divide Port Hills into areas - deployment in teams or individually depending on scale of slope failure • Observations and daily meetings influence deployment • USAR communicate individually with residents and starts to form contact with local community groups	• Hazard identification and rapid qualitative assessment of slope to inform evacuations and lifeline safety continues • Body recovery complete • Daily report to USAR base and CDEM continues • USAR Involvement with daily meetings of geotechnical response continues • USAR start to attend community meetings	• Evacuations completed • Geotechnical contingent of USAR disband after 3 weeks because of no further requirement for evacuation in Port Hills
Geotechnical Professionals	• Hazard identification and rapid Qualitative Slope assessment to assess slope failure risk to dwellings and lifelines • Installation of basic monitoring equipment i.e. pegs, string line for early warning system - monitored hourly • GPS locations of cracks recorded and noted so that information could be passed on to personnel at the local Emergency Operation Centre (EoC) • Aerial reconnaissance undertaken to inform impact assessment • No coordinated process or methodology for slope assessments • Daily meetings at Emergency Operations Centre • Verbal reporting between geotechnical professionals and CDEM • Geotechnical Professions self deploy - deployment guided by information from the public and visual observations • Local knowledge and aerial reconnaissance informed initial deployment • Individual communications between geotechnical professionals and residents	• Hazard identification and rapid Qualitative Slope assessment to assess slope failure risk to dwellings and lifelines – formalised assessment format starts to develop and recommendations for evacuations are passed on to USAR and CDEM • Installation of further monitoring equipment such as survey network and continuous GPS • Monitoring continue several times daily • Emergency slope remediation and stabilisation commences • Daily meetings at opus international consultants (opus) - verbal reporting continues • Small response groups form (2-3 people) for deployment • Deployment informed by CDEM/CCC call centre, information from residents, visual observations and aerial observations • Development of GIS database commences • Mobilisation of further geotechnical professionals expands through contacts and networking • Communication continues on individual basis between geotechnical professionals and residents	• Slope assessments continue with slope monitoring frequency decreasing at some sites where limited post-earthquake movement has occurred • Standard design for mitigation works developed in some sectors - designed as temporary support with deconstructed expected later during the recovery process • Daily Meetings at Opus continue with representatives from CDEM and CCC attend - Some notes or short memos passed on to CDEM or CCC • GNS steps back to technical support role • Nine sectors developed in the Port Hills – sectors appointed to consultancies involved in response - deployment now within sectors • Deployment informed through information gathered at CCC call centre and passed onto geotechnical professionals • Contractors partner with consultancies to undertake work in sectors • Pro forma developed for slope assessment • Development GIS database continues • Data collected during field assessments logged in GIS using pro forma • Aerial photographs become available – remote mapping commences • GPS equipment installed at some loess failure sites • Community meetings set up - communication with public also continues on individual basis • Geotechnical professionals distribute information for welfare assistance where possible	• Mapping and data collection continues for GNS Science risk model • Slope monitoring continues - further monitoring equipment installed • Stabilisation and remediate work continue • Meetings continue at Opus International Consultants – over time these decrease to weekly • Formal notes or short memos become more frequently used CDEM or CCC • Deployment guided increasingly by mapping required for GNS model and hazard mitigation work • GIS database now in use – hazard mapping logged in database • Some changes within allocation of sectors and sector boundaries due to resourcing by consultants • Community meetings continue
CCC	• CCC provide staff for Emergency Operations Centre (EoC)	• CCC Staff Emergency Operations Centre • EoC becoming more aware of issue in Port Hills • Public able to report concerns to CCC (Call Centre)	• CCC staff Emergency Operations Centre • Relationship with PHGG strengthens • CCC call centre pass on information from residents to geotechnical response group	• GNS commissioned to develop risk models. • Development of contractual agreements with geotechnical professionals • Slope failure in the Port Hills identified as long term issue - affects of February earthquake increased the rockfall and cliff collapse hazard in the area. • Natural hazard response sits within CCC with partnership with CERA
Civil Defence	• Building safety evaluation teams activated • CDEM volunteer response team involved in abseil work at cliffs in Port Hills to assist in slope stabilisation • Initially CDEM response was primarily focussed on the extensive liquefaction and lateral spreading which had occurred across Christchurch	• Building safety evaluation continues • EoC and ECC Combine to form Christchurch Earthquake Response Centre • Science liaison involvement with Port Hills response • Cordon more thoroughly managed	• Oversee PHGG response • Christchurch Earthquake Response Centre becomes increasingly aware of situation and extent of damage in the Port Hills. Port Hills became increasingly encompassed in the CDEM response • Port Hills geotechnical email address set up • Fact sheets developed and distributed	• Oversee PHGG response • Management of response continues with increasing involvement from CERA and CCC

Table 3.4: May 2011 - December 2011 Port Hills geotechnical response timeline

2011	Response to earthquake-induced slope failures			
	Civil Defence	**Christchurch City Council**	**Geotechnical Professionals**	**USAR**
May	Civil Defence no longer managing entity – strategic level management passed to CCC and CERA	CCC and CERA work together to coordinate recovery CCC enters into contractual agreements with consultants involved in the Port Hills Geotechnical Group (PHGG) Public Communications becomes fully founded within CCC	Slope assessments undertaken to inform assignment of Section 124 Notices under the Building Act 2004 Hazard mapping and data collection continue for GNS model Stabilisation of source areas continue Involvement in Public meetings continues PHGG restructures	
June	**MM8** **13th June - Earthquake Mw 6.2 - Caused widespread rockfalls, cliff collapse and landslides in the epicentral area**			
	Emergency Operation Centre established for several days - no involvement in Port Hills	Council aims to review status of Building Safety Evaluation notices in Port Hills CCC oversees PHGG Lifeline routes remain priority for reassessment, then building safety evaluation notices Roads closed for debris removal, and stabilisation	Reassessment of slopes within sectors because of further damage to slopes Further building restriction notices (S124 notices) applied Data collection continues for GNS life safety model Development of GNS life safety model ongoing Stabilisation and remediation of slopes continues Tracks and walkways in Port Hills start to be assessed 21st June - Further cGPS sites installed in Port Hills area	
July				
August			16th Aug - Snowfall event >50mm – snow delays stabilisation work in Port Hills Reassessment of S124 Notices continues Hazard mapping and slope monitoring continues Data collection for GNS life safety model continues	
September		Community Meeting commence 2nd Sept - 9700 residential properties in the Port Hills were zoned from white to green, approx 3700 remaining in white zone pending further geotechnical investigations 22nd Sept - Alliance agreement signed for "SCIRT"	Reassessment of S124 Notices continues Hazard mapping and slope monitoring continues Data collection for GNS life safety model continues	
October			1st, 31st Oct - Water level instrument installed in Port Hills to monitor landslide 19th Oct - Rainfall - 50mm rain fell - slips and affects on Port Hills slope stability Reassessment of S124 Notices continues Hazard mapping and slope monitoring continues Data collection for GNS life safety model continues	
November			1st, 3rd Nov - Water level instrument installed in Port Hills to monitor landslide Reassessment of S124 Notices continues Hazard mapping and slope monitoring continues Data collection for GNS life safety model continues	
December		19th Dec - 1600 properties in Port Hills rezoned from white to green zone. 11300 homes green, 2100 white	Reassessment of S124 Notices continues Hazard mapping and slope monitoring continues Data collection for GNS life safety model continues	
	23rd December Earthquakes Mw 5.8 ,6.0- Caused some localised rockfalls and cliff collapse on Port Hills			
			Reassessment of slopes within sectors - further damage to slopes	

3.3.3 Comparison between risk perceptions prior to and after the Canterbury Earthquake Sequence

A review of landslide and seismic hazard and risk in Christchurch prior to the Canterbury Earthquake Sequence in section 3.2 has enabled comparison between the perception of geotechnical hazard prior to 2010, and the geotechnical hazard that was experienced during the Canterbury Earthquake Sequence (CES). The ground motions experienced in the Port Hills during the 22nd February and 13th June 2011 earthquakes significantly exceeded 500-year seismic design spectra and ground motion estimations from the Canterbury probabilistic seismic hazard model. Consequently, post-earthquake response preparation and pre-earthquake land use planning in the Port Hills was not executed anticipating ground motions and subsequent slope failures that were experienced during the 22nd February 2011 earthquake (Table 3.5). This highlights one limitation to the probabilistic seismic hazard model and emphasises the complexity of incorporating low probability earthquakes when taking a probabilistic approach to seismic hazard.

Table 3.5: Estimated PGA from Probabilistic Seismic Hazard model for Canterbury, and observed slope instability prior to the CES, compared with PGA and slope instability experienced in the Port Hills between 4th September 2010 and 13th June 2011 earthquakes (Massey et al. 2012a)

Earthquake	Slope instability in Port Hills	Peak horizontal ground acceleration	Peak vertical ground acceleration
Prior to Canterbury earthquake Sequence	Localised rockfall and loess failure common (Brown and Weeber 1992)	For class C (shallow soil) site conditions (Stirling et al. 2008): • 0.31g estimated for 500-year event • 0.4g estimated for 1000-year event • 0.5g estimated for 2000-year event	
4th September 2010	Few localised rockfalls and loess failure	0.6g at Heathcoate Valley School	0.3g at Cashmere High School
22nd February 2011	Widespread rockfall, cliff collapse, loess failure and retaining wall failure	1.41g at Heathcoate Valley School	2.21g at Heathcoate Valley School
13th June 2011	Widespread rockfall, cliff collapse, loess failure and retaining wall failure	0.6g at Heathcoate Valley School 2.2g near Godley Drive, Sumner	0.2g at Heathcoate Valley School 1.1g near Godley Drive, Sumner

Furthermore, historical evidence did not demonstrate a risk of large scale slope failure such as cliff collapse in the Port Hills; rather historically the most common failure mechanism was localised rockfall. Moreover, the extent of slope failure that occurred after the 4th September

2010 earthquake conformed to previous expectations of slope behaviour in the Port Hills, with minor rockfall and loess failure occurring. Talus at the base of cliffs prior to the CES suggested that shedding of loose material had occurred previously, however at a smaller scale and slower rate than observed during the 22nd February and 13th June 2011 earthquakes. This meant that the widespread slope failure that occurred was unexpected and consequently, there were no planned procedures for coordinating geotechnical response to manage co-seismic slope failure in urban areas. Furthermore, no procedures were developed after the 4th September earthquake as the limited impact on the Port Hills conformed to historic evidence of previous slope failure.

3.3.4 Involvement of organisations in geotechnical response

3.3.4.1 Canterbury Regional Civil Defence and Emergency Management Group

The involvement of the Canterbury regional Civil Defence and Emergency Management (CDEM) group commenced immediately after the 4th September 2010 and 22nd February 2011 earthquakes and remained active throughout the State of Local Emergency (ceased 16th September 2010), and the State of National Emergency (ceased 30th April 2011) respectively. The role of Canterbury Regional Civil Defence and Emergency Management Group was to coordinate the regional emergency response by assessing the impact of the event at a regional scale and developing action plans to support local response. Appendix F provides further detail of the general structure and capabilities of CDEM, and involvement after the 4th September 2010 and 22nd February 2011 earthquakes. The objectives of the CDEM response in relation to earthquake-induced slope failures in the Port Hills are summarised in Table 3.6.

After the 22nd February 2011 earthquake, priorities of CDEM were impact assessment and the protection of life safety through implementing building safety evaluation and building use restrictions in the Port Hills. CDEM science liaison became crucial in the coordination of the geotechnical response after the 22nd February 2011 earthquake because of the scale and complexity of the event. Typically the role of science liaison would involve communicating between scientists and CDEM so that scientific information may inform post-earthquake emergency management. CDEM science liaison became important for ensuring the response from geotechnical professionals was integrated into the CDEM response and that communication was maintained between the two groups. As such science liaison became the CDEM representative at daily meetings held by Urban Search and Rescue (USAR) and the

Port Hills Geotechnical Group (PHGG). Although it was not typically part of the role, science liaison also became involved in communication with residents in the Port Hills until public communication could be included in the capabilities of Christchurch City Council (CCC).

Although additional extensive slope failure was initiated after the 13th June 2011 earthquake, there was no requirement for involvement from CDEM as further protection of life safety could be implemented through the response for the Port Hills Geotechnical Group (PHGG) under the direction of CCC.

Table 3.6: Priorities of Civil Defence and Emergency Management in relation to earthquake-induced slope failures

Timeframe	Objectives
4th September 2010 Earthquake	
No involvement with Port Hills, however active involvement with emergency management in Christchurch CBD, Christchurch suburbs and Selywn and Waimakariri districts.	
22nd February 2011 Earthquake	
1-2 days post-earthquake	• Impact assessment • Body Recovery and rescue • Protection of life safety
3-7 days post-earthquake	• Body Recovery and rescue • Protection of life safety - building safety evaluation increasing priority • Increasing focus on Welfare (in the first days after the earthquake welfare was sustained by communities assisting one another)
1-2 weeks post-earthquake	• Protection of life safety - building safety evaluation continues • Supplying communities with welfare and sanitation
13th June 2011 Earthquakes	
No involvement with Port Hills – geotechnical response in the Port Hills was managed by the Port Hills Geotechnical Group and Christchurch City Council.	

3.3.4.2 Christchurch City Council

Christchurch City Council (CCC) was involved in the geotechnical response since the initiating earthquake on 4th September 2010 when they commissioned local geotechnical professionals to report on the impact in the Port Hills, and manage remediation of slopes that had failed during the earthquake. In the aftermath of the 22nd February 2011 earthquake CCC was primarily involved in emergency management through involvement in local CDEM arrangements, consequently the response directly from CCC was minimal in the immediate aftermath of the event. Over time representatives from CCC became increasingly involved in the Port Hills response as it became apparent the slope instabilities caused by the earthquake were likely to continue to be an issue beyond the duration of the state of national emergency. As such, the CCC was required to become involved in the continuing management of slope failures. The objectives of CCC throughout the response are shown in Table 3.7. The involvement of CCC continued beyond the state of national emergency, and continues at the time of writing this thesis.

Table 3.7: Priorities of Christchurch City Council during geotechnical response

Timeframe	Objective
4th September 2010 Earthquake	
Response during Local State of Emergency	• Provide Staff for Emergency Operations Centre (EoC)
Recovery	• Commission Port Hills impact assessment
22nd February 2011 Earthquake	
1-2 days to 2 weeks post-earthquake	• Provide staff for EoC
1-2 months post-earthquake	• Provide staff for EoC • Coordinate assessment of long term risk and geotechnical response group (Focus on recovery increases)
Recovery	• Provide staff for EoC • Coordinate and oversee assessment of long term risk and geotechnical response group • Manage long term risk associated with Port Hills slope failures
13th June 2011 Earthquakes	
Response	• Coordinate and oversee activities of geotechnical response group

3.3.4.3 Urban Search and Rescue

The role of Urban Search and Rescue (USAR) in an earthquake response includes the protection of life safety by locating and rescuing victims, and using technical expertise to evacuate people from areas at risk from unsafe structures. In the context of the Port Hills, the involvement of USAR was critical because of their authority to enforce evacuations under the NZ Fire Service Legislation. USAR was involved in the emergency response within Christchurch after the 4th September 2010 earthquake, and again after the 22nd February 2011 earthquake.

Immediately after the 4th September 2010 earthquake there was no mobilisation of USAR geotechnical professionals to Port Hills because the minor slope failures that were initiated could be managed within local resources. Some USAR personnel stepped down from their roles 24 hours after the earthquake due to the lack of requirement of their response capability, while others were involved in the removal or stabilisation of unsafe chimneys and inspection of unsafe properties which extended beyond the end of the state of local emergencies that ended on the 16th September 2010.

Immediately after the 22nd February earthquake USAR established an operational base at Latimer Square. Four USAR personnel trained in geotechnical engineering or engineering geology and were deployed to the Port Hills on the afternoon of the 23rd February 2011. The priorities of the USAR geotechnical response included:

- Protection of life safety on lifelines – initiate road restrictions and road closures accordingly,
- Protection of life safety of inhabitants at risk from slope failure – enforce evacuations and initiate restrictions to building use,
- Body recovery (during first week of response).

These priorities were maintained throughout the duration of USAR involvement in the Port Hills. The geotechnical contingent of USAR was disbanded after three weeks post-earthquake because evacuations were then completed in the Port Hills.

3.3.4.4 Geotechnical professionals

Local geotechnical professionals have been involved in the response in the Port Hills since the 4th September 2010 earthquake occurred. The minimal impact the 4th September 2010 earthquake had on the Port Hills meant that the response required could be facilitated through the Christchurch City Council and locally contracted consultants. In the aftermath of the earthquake, local geotechnical professionals were deployed to the Port Hills with local knowledge regarding locations where previous slope failures had occurred. This led to the evaluation of slope stability to provide advice for remediation and risk management.

Due to the widespread slope failure initiated by the 22nd February 2011 earthquake the involvement of geotechnical professionals was significantly more extensive and required the involvement of GNS and geotechnical professionals sourced locally and from locations outside of Christchurch. Consequently a response group was formed of geotechnical experts and professionals who were aware of the life safety risk associated with the initiated slope failures. The objectives of local geotechnical professionals are provided in Table 3.8.

Table 3.8 : Priorities of local geotechnical professionals during response to earthquake-induced landslides

Timeframes	Objectives
4th September 2010 Earthquake	
Response and Recovery	• Protect lifelines and major roads in the Port Hills • Impact assessment
22nd February 2011 Earthquake	
Response 1-2 days post-earthquake (During National State of Emergency)	• Impact assessment • Protection of life safety – rapid assessment of slopes to make recommendations for evacuations
Response 3-7 days (During National State of Emergency)	• Protection of life safety – rapid assessment of slopes to make recommendations for evacuations and building safety notices • Coordinate and expand group to improve response
Response 1-2 weeks (During National State of Emergency)	• Protection of life safety – rapid assessment of slopes to make recommendations for evacuations and building safety notices • Development of GIS database
Response 1-2 months (During National State of Emergency)	• Protection of life safety • Data collection for GNS Life Safety models • Requirement for slope assessments to inform Building Safety Restrictions decreases
Recovery	• Protection of life safety • Data collection for GNS Life Safety models
13th June 2011 Earthquakes	
Response	• Protection of life safety through rapid assessment of slopes and making further recommendations for evacuations and building safety evaluations

In the immediate aftermath of the earthquake, there were no established methods or statutory requirement for coordinating slope assessments with building safety evaluation and protection of lifelines. As the geotechnical professionals became involved with USAR and CDEM, systems for response coordination developed and local consultants formed the Port Hills Geotechnical Group (PHGG) within the first week of the response. Initially the group functioned under auspices of CDEM during the state of national emergency, and received technical support from GNS. During the recovery phase each local consultancy was engaged in a contractual arrangement with the Christchurch City Council to undertake geotechnical work in the Port Hills including slope assessments, slope stabilisation and rockfall modelling. The PHGG were involved in the geotechnical response in the Port Hills after subsequent aftershocks following the 22nd February 2011, and continued until early 2013.

3.3.4.5 Interactions between organisations

The relationships and interactions between organisations involved in Port Hills slope failure hazard have evolved and developed throughout the Canterbury Earthquake Sequence. Prior to the earthquake sequence the main participating organisations that were involved in slope failure hazard in the Port Hills were the Christchurch City Council (CCC), Environment Canterbury (ECan), GNS and local geotechnical professionals (Figure 3.3).

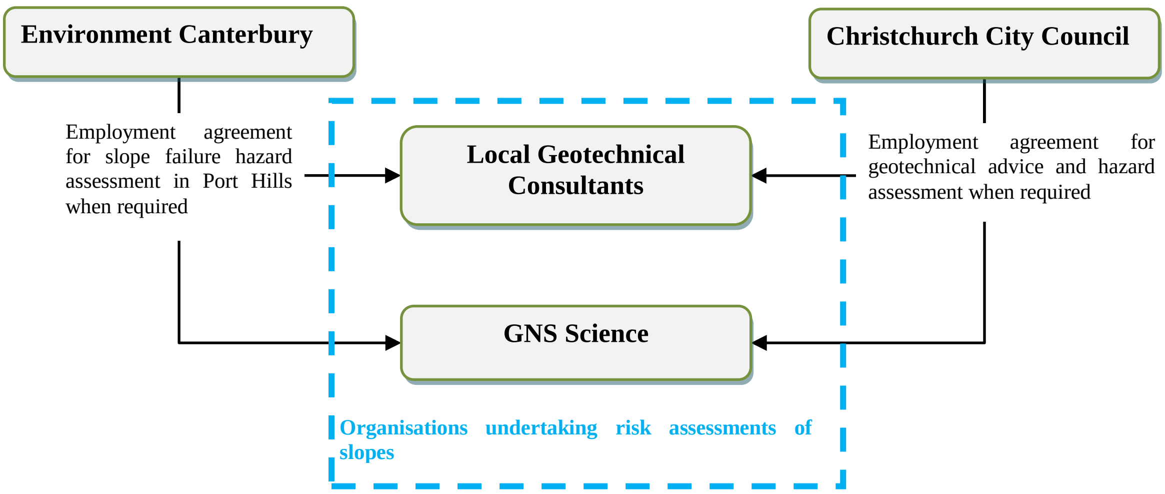


Figure 3.3: Interaction of organisations prior to earthquake sequence

The involvement of strategic organisations such as CCC and Ecan took place under legal requirements of local and regional councils to address natural hazards under government legislation (Table 3.9). Because of this requirement, local and regional authorities contracted geotechnical consultants to undertake slope failure risk assessment and hazard identification in the Port Hills, and provide recommendations for risk management options such as rockfall protection and land use planning.

Table 3.9: Legislation prior to the Canterbury Earthquake Sequence

Legislation	Impacts on Port Hills slope failure hazard and risk
Resource Management Act (1991)	• Section 30 of the RMA (1991) requires local and regional authorities to control the use of land to avoid to mitigated impacts of natural hazards
Civil Defence Emergency Management Act (2002)	• Local and regional authorities prepare an emergency management plan i.e. Canterbury Regional Civil Defence and Emergency Management Recovery Plan which was in place when 4th September 2010 earthquake occurred
Building Act (2004)	• Section 71 of Building Act requires building consent authorities (e.g. local council) to refuse to grant building consent for construction on land is subject to natural hazard. Natural hazard is defined as erosion, slippage, falling debris, subsidence and inundation.

The occurrence of the initiating event in the Canterbury Earthquake Sequence (the 4th September 2010 earthquake) did not change the use of contractual arrangement between CCC and local geotechnical professionals because the minor impact that the earthquake had on the Port Hills could be managed with existing consulting capability (Figure 3.4). Although it did not directly impact the response in the Port Hills, CCC became involved with the Canterbury Earthquake Recovery Commission after the passing of the Canterbury Earthquake Response and Recovery Act, 2010. A description of the act and impacts on the response are provided in Table 3.10.

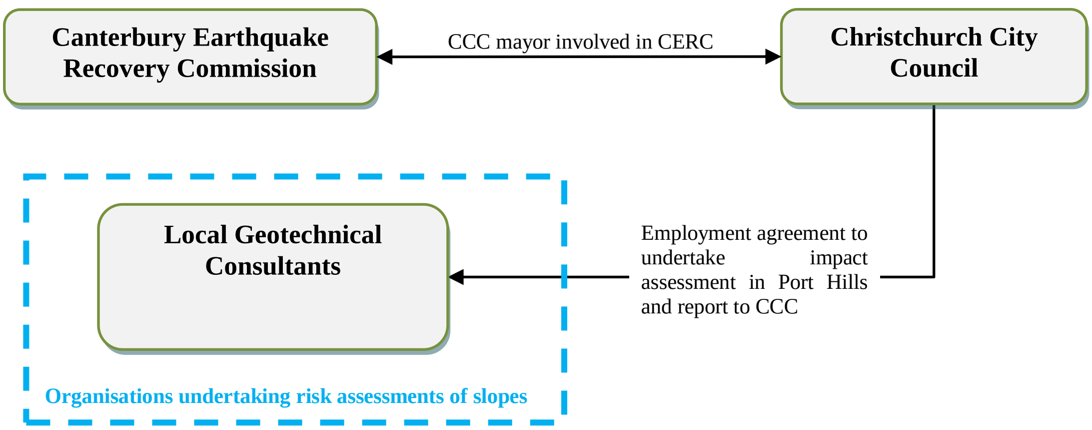


Figure 3.4: Interaction of organisations within the Port Hills response after 4th September 2010 earthquake

Table 3.10: Legislation passed during the Canterbury Earthquake Sequence

Legislation	Description	Impacts on Port Hills slope failure hazard and risk
Post 4th September 2010 earthquake		
Canterbury Earthquake Response and Recovery Act, 2010 (CERR 2010)	• CERR 2010 overruled the existing pre-earthquake Canterbury Regional Civil Defence and Emergency Management Recovery Plan and endorsed the Canterbury Earthquake Recovery Commission (the commission) • The commission was established to provide advice to central government in relation to prioritising resources and funding allocations (See glossary) • Aimed to assist the response and recovery to the earthquake as from a strategic perspective the capabilities of existing legislation did not provide the necessary resources for the response	• Limited impact on Port Hills - work was undertaken under client and contractor engagement. • Establishment of the commission made it difficult for some scientists and science liaison to identify where to request funding from. Many scientists felt that the role of the commission was not clearly defined.
Post 22nd February 2011 earthquake		
Canterbury Earthquake Recovery Act, 2011 (CERA 2011)	• CERR (2010) was repealed by the CERA (2011) in April 2011 • CERA (2011) enabled the recovery to be handed over to the new government authority, Canterbury Earthquake Recovery Authority which was established under the New Zealand State Sector Act of 1988 • Purpose of CERA was to lead a locally focussed and co-ordinated recovery following the February 2011 earthquake by providing a framework for public entities to work within community organisations, non-governmental organisations, iwi and the private sector (Controller and Auditor General 2012)	• Endorsed partnership agreement between CCC and CERA • Enables CCC and CERA to co-manage and co-fund infrastructure rebuild and risk assessment in Port Hills • Initially required local authorities and CERA to define their roles within the response and recovery in the Port Hills and Christchurch.

At least 48 hours after the 22nd February 2011 earthquake the geotechnical professionals became involved in the response in the Port Hills by assessing slopes and providing verbal recommendations to USAR and CDEM for evacuations, road closures and building safety evaluation notices (Figure 3.5). Representatives from CCC and CDEM science liaison attended meetings held by USAR and geotechnical professionals, however the interaction between these organisations was limited within the first week after the earthquake as the geotechnical response was operating independently of CDEM. Once interaction between CDEM and geotechnical professionals increased, science liaison began to pass information from residents to geotechnical professionals regarding areas where slope failure had reportedly occurred in the Port Hills which increased the integration of the geotechnical response within CDEM response.

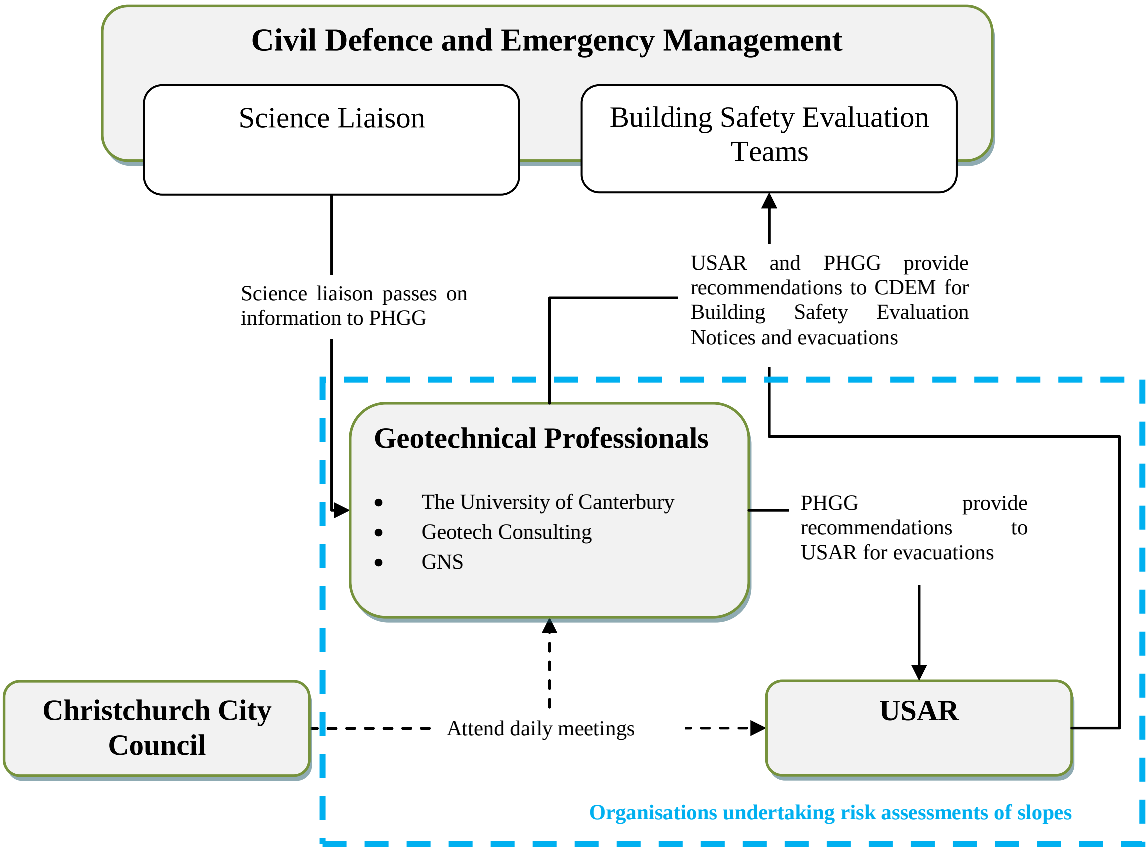


Figure 3.5: Interactions of organisations in response in Port Hills approximately 48 hours after 22nd February 2011 earthquake during the Canterbury Earthquake Sequence

Approximately one week after the earthquake, a framework of response was beginning to develop with the division of sectors in the Port Hills. This formed the foundation of the operating structure for the Port Hill Geotechnical Group (PHGG) and changed the interaction of organisations. Concurrently, GNS stepped back from PHGG and employed a role of technical support. GNS then started to develop a life safety risk model for rockfall and cliff collapse for Christchurch City Council (CCC), which formalised the relationship between the two organisations into a contractual arrangement (Figure 3.6). PHGG continued to assess slope failures and provide verbal recommendations to USAR and CDEM for evacuations and building safety evaluation notices. The requirement for this interaction decreased during the three weeks that USAR was involved in the geotechnical response, as the requirement for the enforcement of evacuations reduced.

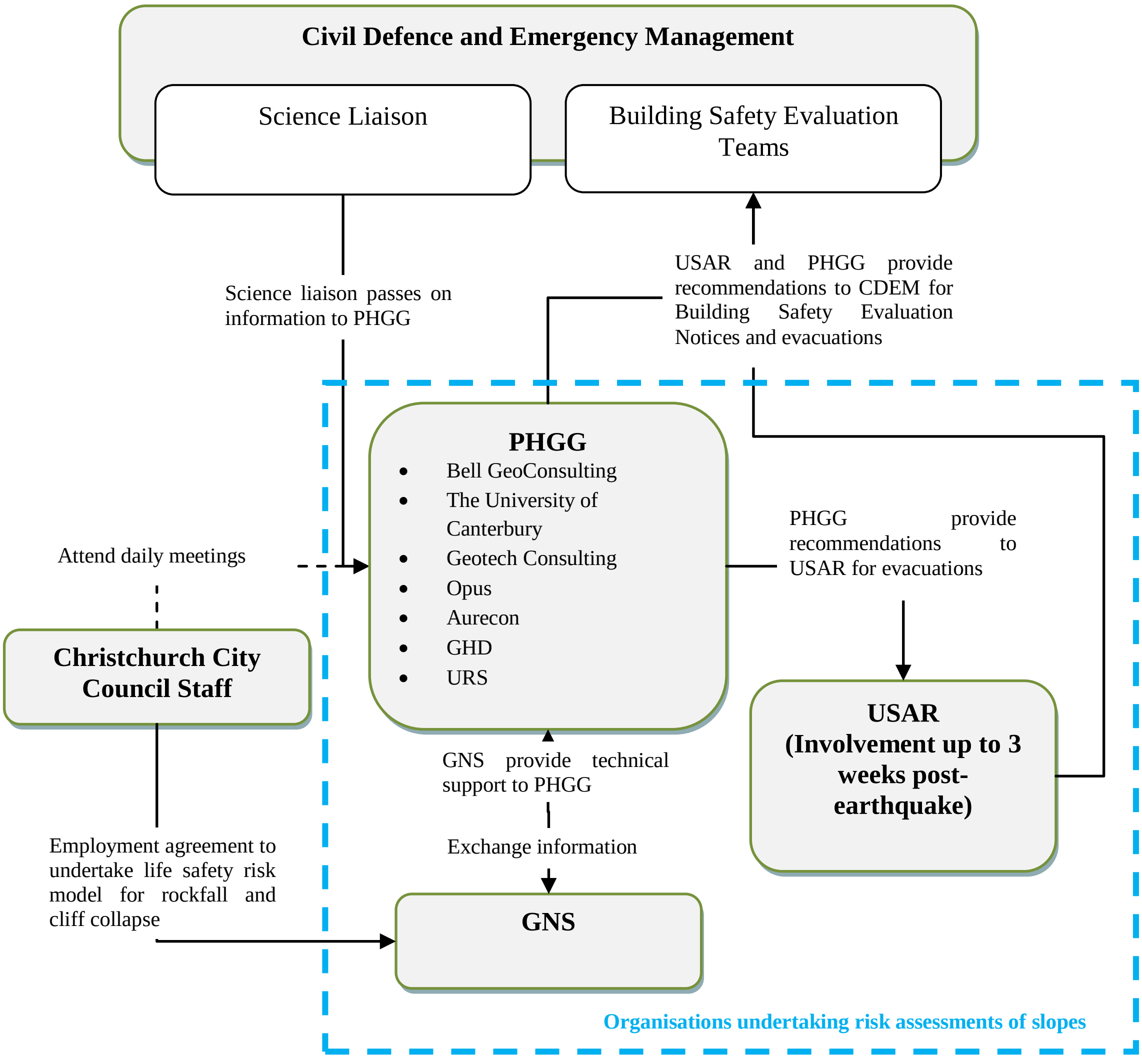


Figure 3.6: Interaction of organisations in the Port Hills response from approximately one week after the 22nd February 2011 earthquake

As the requirement for evacuations decreased and USAR became less involved in the response, PHGG became increasingly involved in data collection to inform the life safety risk model developed by GNS. By the end of the state of national emergency (30th April 2011) contractual agreements between CCC and geotechnical consultancies were developed which formalised the relationship between the two organisations. The framework for interaction (Figure 3.7) which was established at the end of the state of national emergency was maintained throughout the response to the 13th June 2011 earthquake and continued until PHGG ceased in 2013. After the state of national emergency ceased, and the Canterbury

Earthquake Recovery Act (2011) repealed the Canterbury Earthquake Response and Recovery Act (2010), the CCC and Canterbury Earthquake Recovery Authority (CERA) began to oversee the recovery of the city. Because slope failure in the Port Hills was expected to be a long-term issue for Christchurch City, and CERA had a limited timeframe for involvement, the majority of the management of slope failure was maintained by CCC.

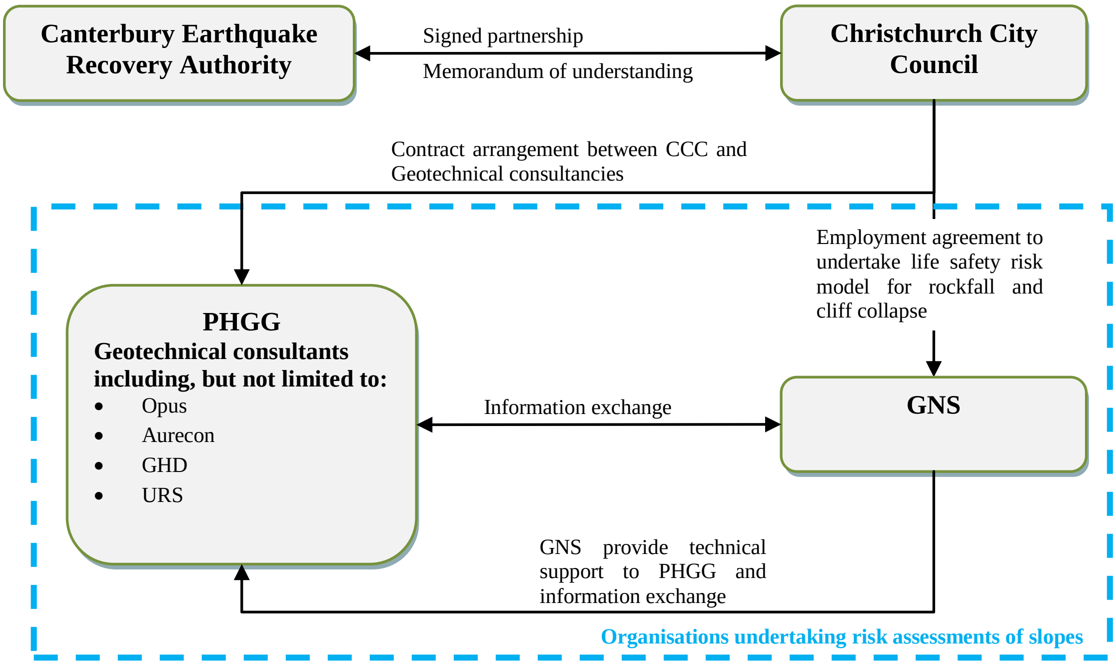


Figure 3.7: Interactions of organisations in Port Hills response after state of national emergency ceases (30th April 2011) after the 22nd February 2011 earthquake

3.4 Key themes from the geotechnical response

Themes which had significant contribution to the geotechnical response to the Canterbury Earthquake Sequence (CES) have been identified from interview information. Examination of these themes sheds light on the progression of the response and presents key milestones that were pivotal in the execution of the response. The 22nd February 2011 earthquake has been the most influential event in the analysis of the CES as it required the largest contribution of involvement from the geotechnical community.

3.4.1 Coordination of geotechnical response

Coordination of the geotechnical response to earthquake-induced slope failure was a significant theme in the CES due to the influences that changes in the coordination had on the execution of the response from a management level and tactical level. Table 3.11 outlines notable changes in the coordination of the geotechnical response which have had implications for the processes utilised in the response such as deployment of geotechnical professionals, field data collection and communication between organisations.

Table 3.11: Example of coordination developments in Canterbury Earthquake Sequence

Coordination	Timeframe	Implications for geotechnical response
Post-4th September 2010 Earthquake		
Development of the Canterbury Earthquake Recovery Commission and CERR (2010)	14th September 2010	Pre earthquake recovery plan needed support and coordination from government
Post 22nd February 2011 Earthquake		
Integration of Emergency Operation Centre (EoC) and Emergency Coordination Centre (ECC) to form Christchurch Earthquake Response Centre (See Appendix F for further detail)	Approx. 3 days post-earthquake	Although this did not directly affect the response in the Port Hills, however it did result in the requirement for new coordination systems to form during the aftermath of the earthquake
Collaboration between USAR and PHGG	Approx. 2 days post-earthquake	Development of response framework where geotechnical professionals assess slopes and provide recommendations to USAR for evacuations
Development of a local geotechnical response group	Approx. 2 days post-earthquake	Coordination between geotechnical professionals improved with
Division of the Port Hills into sectors	Approx. 1 week post-earthquake	Coordinated deployment in Port Hills Reduce duplication of assessments All areas of Port Hills included in response
Development of standard slope assessment format	Approx. 1 week post-earthquake	Consistency in data collection and slope assessment techniques
Development of a GIS database for management and analysis of field data	Approx. 1 week post-earthquake	Produce maps to inform PHGG daily meetings and assist coordination Maps show: known extent of slope failure, sectors division, reports from Port Hills residents.
Daily/Regular meetings	Approx. 2 days post-earthquake and continued weeks after earthquake	Facilitate coordination and communication within geotechnical response group
Contractual agreements between CCC and PHGG consultants	After state of national emergency	CCC oversees work in Port Hills

3.4.1.1 Initial coordination of geotechnical response

Coordination became a predominant concern in the immediate aftermath of the 22nd February 2011 earthquake when local geotechnical professionals self-mobilised to inspect slope failures, and to provide input into building access restrictions and evacuations. In the first instance, coordination between USAR and local geotechnical professionals was not established due to the self-mobilisation of geotechnical professionals or at the request of clients. As such, initially the response was undertaken on an individual basis and consequently coordination between organisations was minimal. Furthermore, geotechnical professionals found it difficult to discern who to report their observations to as there was no overarching management of the geotechnical response.

On the 23rd and 24th February 2011 coordination between geotechnical professionals started to increase. Personnel from the Christchurch City Council (CCC) and local geotechnical professionals identified the need for a geotechnical response group to be formed. The utilisation of networking and contacts within the geotechnical community aided the development and expansion of the group. By the 24th February the geotechnical response began to form contact with geotechnical representatives from USAR and a reporting procedure developed between the two organisations. Some geotechnical professionals involved in the response had no previous experience or training in emergency response, and were unaware of the roles of Urban Search and Rescue (USAR) and Civil Defence and Emergency Management (CDEM). Consequently within the first week of the response emphasis on role definition became important for the enforcement of evacuations, which facilitated the system for response between USAR and PHGG. The arrangement for communication between geotechnical professionals, USAR and CDEM is presented in Figure 3.8.

Days after the earthquake, aerial photography by New Zealand Aerial Mapping was used to provide visual information of the area and enable geotechnical professionals to identify land damage in the Port Hills. Within the first week after the earthquake it became difficult to obtain the aerial photographs because Dead Victim Identification (DVI) had not been completed. This hindered the ability of geotechnical professionals to remotely map spatial placement of slope failures to gain an understanding of the impact of the earthquake.

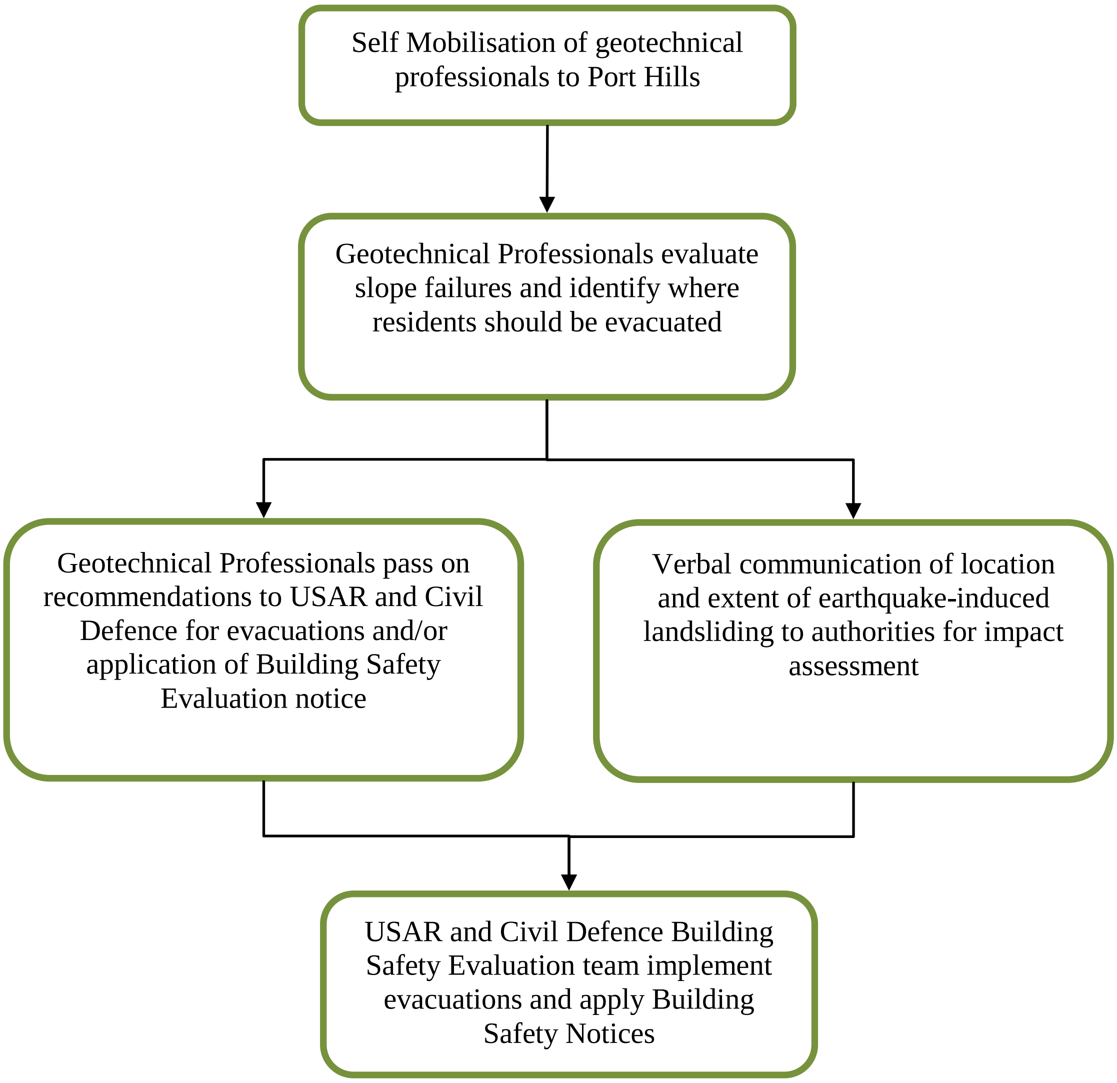


Figure 3.8: Arrangement for communication between PHGG, USAR and CDEM during the geotechnical response days after the 22nd February 2011 earthquake.

The collaboration between local geotechnical professionals and USAR became imperative for the execution of the response due to the scale of slope failure in the Port Hills. While USAR's role in the response was temporary and focused largely on victim recovery, it was important that the team was present so that evacuation could be legally enforced. The demand for geotechnical response could not be met by local resources alone and consequently consultancies deployed geotechnical professionals from other areas of New Zealand which was supported by CDEM and private clients.

Despite the initial involvement of strategic level organisations such as CCC and CDEM, the geotechnical response operated detached from the Civil Defence and Emergency Management response during the emergency phase. Geotechnical professionals involved in

PHGG maintained a self-sufficient structure when managing geotechnical response activities. From the perspective of the geotechnical professionals this worked well as they had the skills and knowledge to address the issue of risk to life safety from coseismic landsliding

3.4.1.2 The role of communication within coordination

Communication was an element of the geotechnical response that was spoken of frequently in interviews. This was primarily because the progression and coordination of the geotechnical response was greatly influenced by communication. As there were no pre-existing processes in place to guide the geotechnical response, pathways for communication between geotechnical professionals, Urban Search and Rescue (USAR) and Civil Defence and Emergency Management (CDEM) were required to form in the aftermath of the earthquake. This hindered coordination internally between geotechnical professionals, and externally between geotechnical professionals and with CDEM. Table 3.12 provides examples of when communication influenced the geotechnical response coordination.

Communication was facilitated through daily meetings which enabled the group to coordinate deployment, data collection, slope assessments, distinguish roles and create contacts within the group. Meetings were also an opportunity for information exchange around hazard locations and areas that had been evacuated. Written records of decisions and observations in the first months after the earthquake were limited however an up to date contact list became important during this time as staffing changes within the PHGG was common.

After the development of sectors one week post-earthquake, it became important that meetings of the PHGG continued so that information was exchanged between sectors and consultancies. Daily meetings became important in facilitating coordination of the geotechnical response. It was important that Christchurch City Council (CCC) representation was present at meetings with the geotechnical response group because it facilitated a conduit between the interests of the council and the activities of the group of geotechnical professionals. Meetings were also attended by a CDEM Science liaison representative who coordinated between geotechnical professionals that were responding in the Port Hills, and the CDEM response establishment in the Christchurch City Art Gallery. This enabled the technical capabilities of the volunteering geotechnical professionals to be incorporated into the emergency response. Over time the frequency of meetings decreased as the processes for slope assessments and data collection were in place.

Table 3.12: Examples where communication influenced coordination of geotechnical response to the 22nd February 2011 earthquake

Example	Implications for response in Port Hills
Although a formal communication process was present between the EoC and the USAR Command, early in the response to the 22nd February earthquake the flow of information was not fluid	• Geotechnical USAR personnel reported back to the EoC individually with their observations from the Port Hills – Impact of earthquake on Port Hills was not fully appreciated by CDEM initially
Days after the 22nd February 2011 some geotechnical professionals found it difficult to distinguish who in the EoC observations should be reported to and what response processes local geotechnical response were required to adhere to.	• Strained communication between some local geotechnical professionals and CDEM • Geotechnical response detached from CDEM
Communication within the geotechnical group developed over the first weeks of the response.	• Formation of PHGG • Coordination within deployment i.e. development of nine sectors
Daily meetings of PHGG	• Facilitated communications within the group and with entities such as USAR, CDEM and CCC • Encourage deployment coordination
Science liaison reported back to CDEM daily.	• Situation reports were passed through the emergency management lines to inform CDEM of progress of geotechnical response • Information was communicated to the CCC Call Centre so that information could be passed on to residents in need of information.

3.4.1.3 Development of sectors in the Port Hills

Although communication between geotechnical professionals was improving days after the earthquake, deployment coordination continued to remain problematic. Initially deployment was influenced by observations made during ground reconnaissance, aerial reconnaissance and communication with residents. Throughout the first week after the earthquake a deployment system developed where public enquires were passed onto geotechnical professionals through CDEM or CCC. Responders within the geotechnical group would then prioritise the sites and deploy to assess the hazards and potential risk that slope failures posed to the life safety of residents.

However, the lack of procedures for deployment resulted in the duplication of site assessment which hindered the timeliness of the response and resulted in inefficiencies in the utilisation of resources. Consequently approximately one week after the February earthquake the Port Hills were divided into nine sectors based on geomorphological features such as ridgelines and valleys. Sectors were assigned to consultancies involved in the geotechnical response group. Once a consultancy was assigned a sector it was their responsibility to assess slopes within that area. Table 3.13 shows the list of sector locations, sector consultancies and principle geotechnical issues. Information from residents who had called the Christchurch Earthquake Response Centre would be directed to the consultancy responsible for that sector (Figure 3.9). An example of the Port Hills sector map has not been included in this document due to confidentiality requirements from Christchurch City Council.

Table 3.13: Port Hills sectors during the state of national emergency (Macfarlane and Yetton 2013)

Sector	Area	Team	Principle geotechnical issues
1	Sumner and East	URS/SKM	Cliff Collapse, boulder roll
2	Clifton Hill	Aurecon	Cliff Collapse, mass movement, boulder roll
3	Redcliffs	Geotech Consulting	Cliff Collapse
4	Mt Pleasant	University of Canterbury/Bell GeoConsulting	Retaining wall failure, boulder roll, cracking
5	Heathcote Valley	Opus	Boulder roll
6	Lyttelton	University of Canterbury/Bell GeoConsulting	Boulder roll, retaining wall failure
7	Avoca/Huntsbury	GHD	Boulder roll, ground cracking
8	Inner Harbour	Aurecon	Boulder roll
9	Cashmere	University of Canterbury/Bell GeoConsulting	Ground cracking, boulder roll

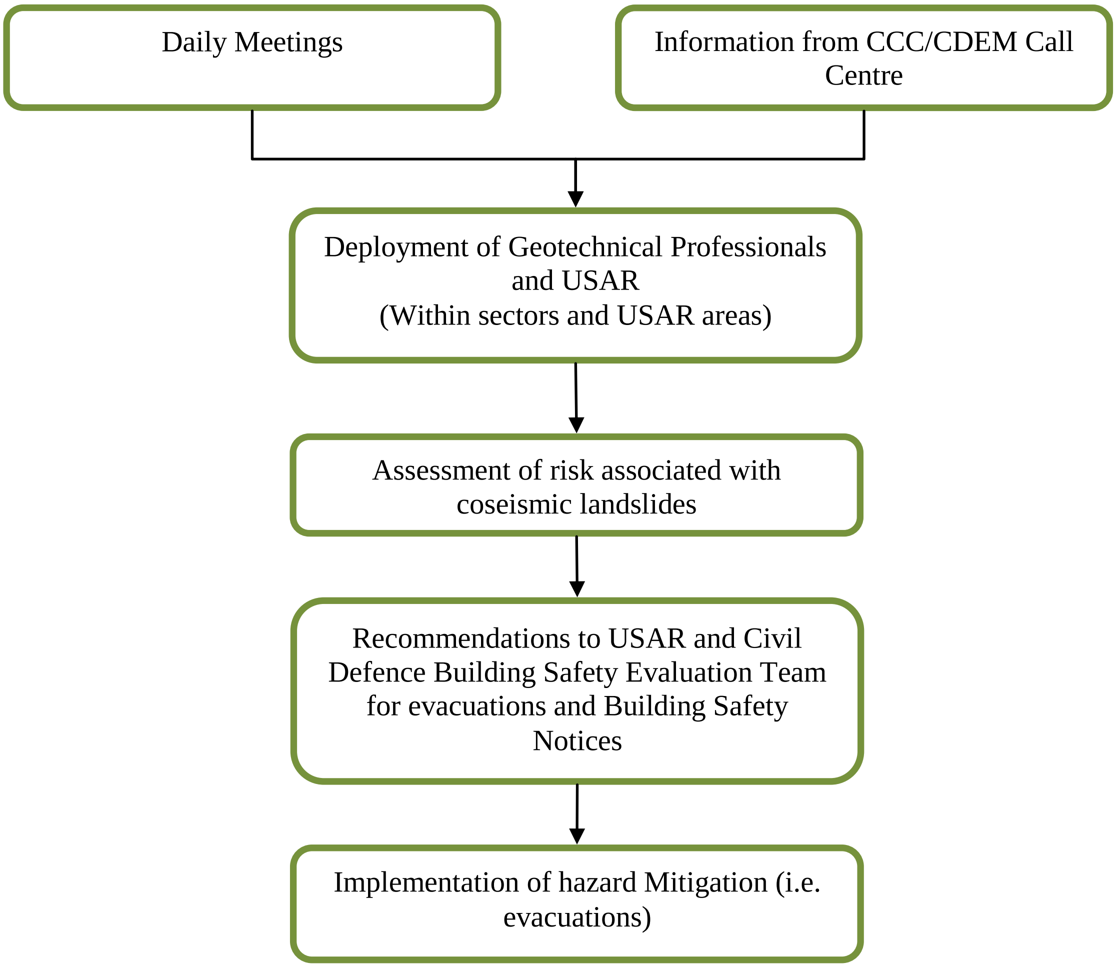


Figure 3.9: Geotechnical response process after the development of sectors one week after the 22nd February 2011 earthquake, until approximately three weeks post-earthquake

USAR also utilised a similar sector system and deployed both on an individual basis and in a group depending on the situation that needed assessing. Upon the development of sectors in the Port Hills, GNS changed their role in the response to providing technical support to the Port Hills Geotechnical Group (PHGG). This allowed GNS to focus on the scientific and research-based response which ensured that data of an ephemeral nature could be collected.

The need for a centralised database was identified within the first week of the response. Approximately one week after the earthquake a Geographic Information Systems (GIS) data base was established by GNS using data sets such as property boundaries, street maps, and postal addresses gathered from the CCC and Environment Canterbury. Based in the Christchurch Earthquake Response Centre the database was used to record and manage information gathered by the emerging geotechnical group. It allowed the production of maps to aid and inform decisions within the response, and enabled data to be passed on to CDEM and Christchurch City Council (CCC) in a suitable format. Initially the database was developed essentially by one GIS expert however, the size of the project required additional GIS experts to assist. It was several days before additional GIS technicians and resources became available.

Several geotechnical consultants involved in the response used their own internal GIS capability to manage and record data that could then be passed onto the GNS database and incorporated into the larger data analysis. Months after the earthquake, a system was established where geotechnical professionals could use an electronic device such as an ipad to record information in the field and upload it directly to the GIS database. This was useful because it reduced the need for uploading data manually into the database.

3.4.1.4 Coordination during earthquake recovery

Throughout late March and April 2011 Christchurch City Council (CCC) became increasingly active and influential in the coordination of the Port Hills Geotechnical Group (PHGG). When the state of national emergency ceased (30th April 2011) the group needed direction and guidance to continue slope assessments and data collection and contractual agreements were established between the Christchurch City Council and consultancies in the PHGG. During this time, the Canterbury Earthquake Recovery Authority (CERA) became increasingly more interested in the Port Hills response.

As the requirement for the PHGG was expected to last for years, the organisation of the group needed to be improved to best sustain and utilise resources and skill sets. The internal coordination of the PHGG changed with the formation of a leadership team and an engineering team to optimise the use of leadership and technical capability. Leaders were selected for each sector in the Port Hills and became responsible for managing the geotechnical activities in their area. The appointment of sector leaders within the group introduced an operating structure outlined in Figure 3.10. Sector leader meetings occurred regularly with the aim to standardise the approach between sectors and maintain communication between consultancies. At this point, external peer review was recommended to the CCC by the PHGG to oversee and guide the geotechnical activities.

After the 13th June 2011 earthquake the systems for the geotechnical response were in place and there was no need to develop coordination between response entities because this had been established after the 22nd February 2011 earthquake. By the time the 13th June earthquakes occurred, CCC was coordinating contracts with consultants to undertake mapping and mitigation works. By 2013, CCC developed a list of geotechnical consultancies that could provide geotechnical engineering advice.

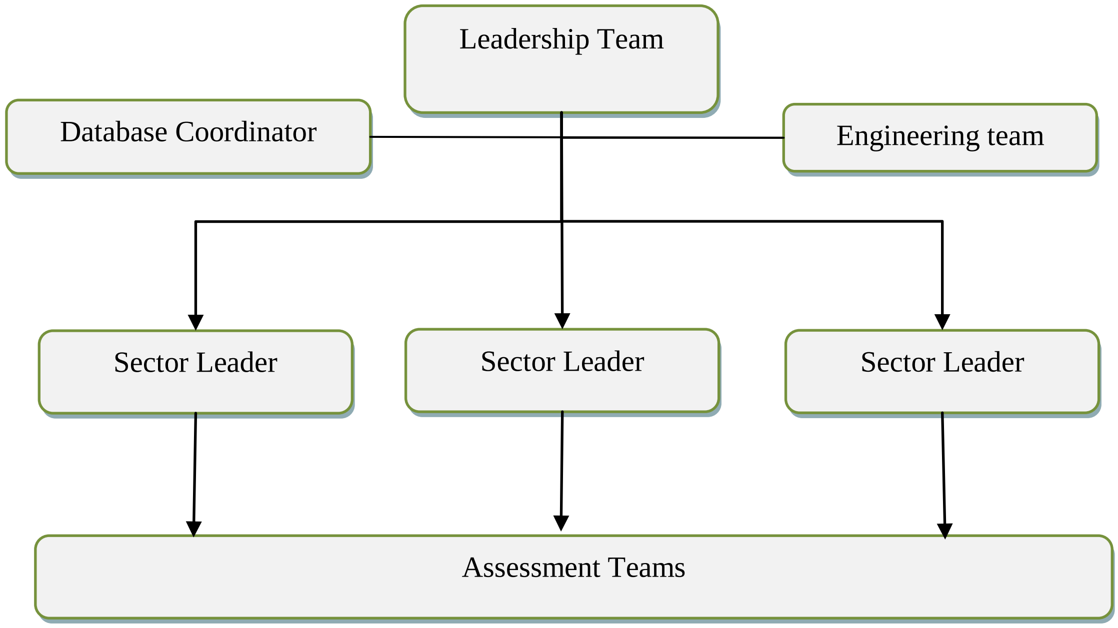


Figure 3.10: Operating structure for geotechncial response to the 22nd February 2011 earthquake after the state of national emergency ceased (30th April 2011)

3.4.2 Life safety

The threat that earthquake-induced rockfall, cliff collapse and loess failure posed on inhabitants and road users in the Port Hills meant that life safety became a significant focus throughout the response to the CES. In this thesis, life safety refers to the both the life and physical well-being of individuals. After the 4th September 2011 earthquake risk to life safety was addressed through the deployment of a local geotechnical professional to assess the impact of rockfall, which was managed with road use restrictions and road closures. Weeks after the earthquake the CCC commissioned the same local geotechnical professionals to report on the impact that the earthquake had caused on the Port Hills and whether land use planning and residential development practices should be changed as a result of the affects of the earthquake. The report concluded that in light of the minimal impact to the Port Hills after a large earthquake event, no changes to land use planning would be required and indicatively no long-term life safety issues were present.

Immediately after the 22nd February 2011 earthquake, protection of life safety in the Port Hills became the priority for CDEM, USAR and the local geotechnical response group due to the perception that earthquake-induced slope failures posed imminent life safety risk to residents. In the immediate aftermath of the earthquake it was uncertain whether further aftershocks; static conditions or rainfall could induce further rockfall, cliff collapse and loess failure. Consequently areas where failure had occurred needed to be assessed to quantify the risk to life safety and enforce techniques such as road closures and restrictions, evacuations and building use restrictions.

3.4.2.1 Assessment of life safety risk

In the immediate response to the 22nd February 2011 earthquake the aim of the geotechnical response was to determine as quickly as possible where people were at risk so that PHGG could provide recommendations to USAR and CDEM of locations where evacuations, road restrictions, or building safety placards would be required (Figure 3.11). To achieve this, the initial slope assessment procedure executed by geotechnical professionals included rapid identification of areas of significant ground damage in residential areas in the Port Hills. Due to the extent of rockfall, cliff collapse and loess failure which had occurred there was a high demand for local geotechnical professionals to participate in rapid site assessments.

Immediately after the 22nd February 2011 earthquake, risk to life safety was assessed qualitatively based on expert opinion and previous knowledge and experience by geotechnical professionals responding in the field. Qualitative assessment allowed for speed of assessments and rapid coverage of the area affected. Information from interviews indicated that the time taken to assess each failure was variable depending on the extent and intricacies of the slope failure. At this stage, monitoring data was limited to what had been collected since the earthquake.

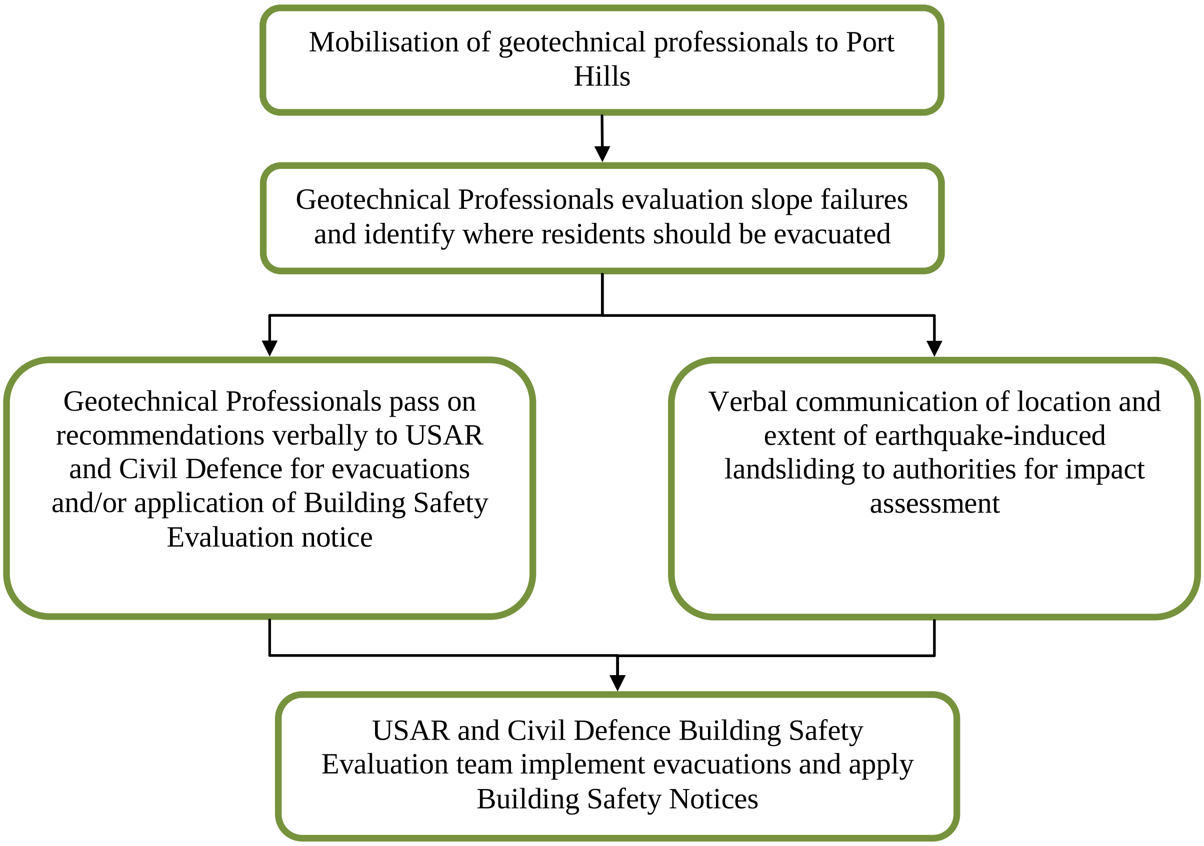


Figure 3.11: Process for slope assessment informing hazard management during the geotechnical response one week after 22nd February 2011 earthquake

During the initial response areas that were considered at risk included:

- Properties or roads at the top of slopes affected by cracking and displacement of material,
- Properties or roads at the base of slopes that were affected by compression features, adjacent to material inundation, or have been inundated themselves.

Observations included in qualitative slope assessments for each failure type are listed in Table 3.14. Assessments also included observations of potential source areas, topography, vegetation, and proximity of slope failures to elements at risk. USAR developed a similar list of critical observations to record during the assessment. Basic slope monitoring equipment including string lines and spray paint markers across sites were installed where movement had occurred to provide information regarding the slope behaviour which contributed to an estimation of the likelihood of failure. Regular measurements of monitoring equipment were recorded to establish a flow of information regarding the slope movement and behaviour, and shed light on the mechanisms of failure at the site. Continuous GPS and survey networks were installed at some sites in order to regularly monitor any further movement.

Table 3.14: Assessment observations for each slope failures during the geotechnical response to the 22nd February 2011 earthquake

Slope failure type	Assessment observation
Cliff Collapse	• Crack locations and aperture • Location and extent of debris inundation • Rock Mass condition • Monitoring of slope movement i.e. crack apertures, extent, magnitude and direction of displacement
Rockfall (boulder roll)	• Rock mass condition • Rockfall run out path • Boulder mapping • Potential Source areas
Loess failures	• Crack locations and aperture • Location of compression features (toe bulging) • Monitoring of slope movement – extent, magnitude, direction of displacement

Categorisation of slope failures in the Port Hills was conducted through visual observations made on site corresponding to failure features such as cracking and toe bulging as there was no subsurface information available. The aim of defining the failure mechanism was to distinguish what hazards were associated with these features and determine what data needs to be collected. An interpretation of the risk management process which was implemented immediate post-earthquake is presented in Figure 3.12.

During the first week of the response to the 22nd February 2011, emphasis was placed on the identification and characterisation of the slope failure hazard to estimate a likelihood of failure, which subsequently informed implementation of hazard management techniques. Risk assessment was undertaken through consideration of the potential impact on critical infrastructure or dwellings located in the affected area. The evaluation of risk in rapid response was quantified by whether there was potential for loss of life or injury if the hazard identified was to fail further. This was because earthquake-induced slope failures presented imminent risk which was exacerbated by uncertainty around the likelihood of further failure or reactivation.

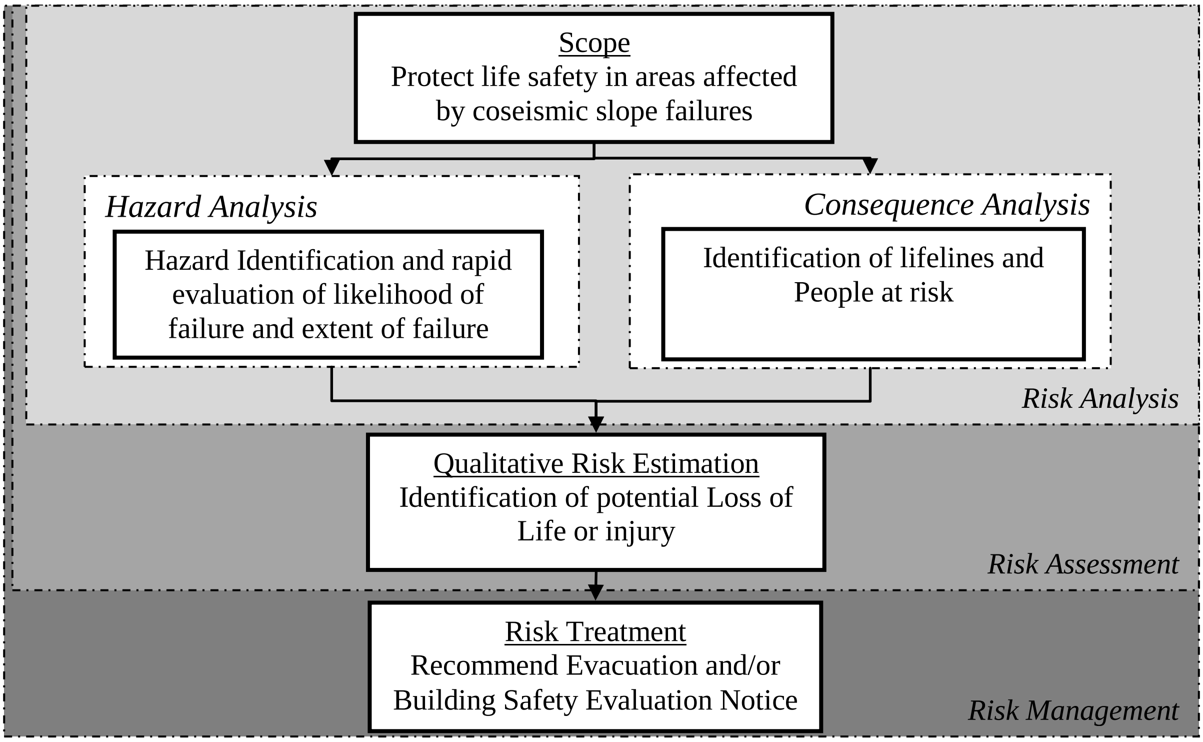


Figure 3.12: Interpretation of emergency risk assessment methodology for earthquake-induced slope failure implemented during the immediate response to the 22nd February 2011 earthquake

Initially after the earthquake the uncertainty around defining the failure mechanism was significant due to the lack of detailed information, however this decreased over time as slope behaviour was further monitored. Lack of understanding and knowledge around the failure mechanism at some sites also influenced the perception of risk, and in some cases this may have resulted in an overly conservative risk management approach which consequently can result in the unnecessary displacement of people. Uncertainty was reduced through discussions between USAR and geotechnical professionals regarding the potential risk at each site. This discussion acted as a form of informal peer review to ensure that the most appropriate risk management decision possible was made for each site.

3.4.2.2 Implementation of standard slope assessment format

Approximately one week after the 22nd February 2011 earthquake, a formalised slope assessment reporting format was developed by several of the geotechnical professionals involved in the response. The format was developed to improve consistency of risk assessment of earthquake-induced slope failures and outlined a methodology for qualitative slope assessment of the potential effect or consequence of the failure and the likelihood of failure to guide treatment decisions. The process for the reporting format is outlined in Figure 3.13 and the standard slope assessment format attached in Appendix G.

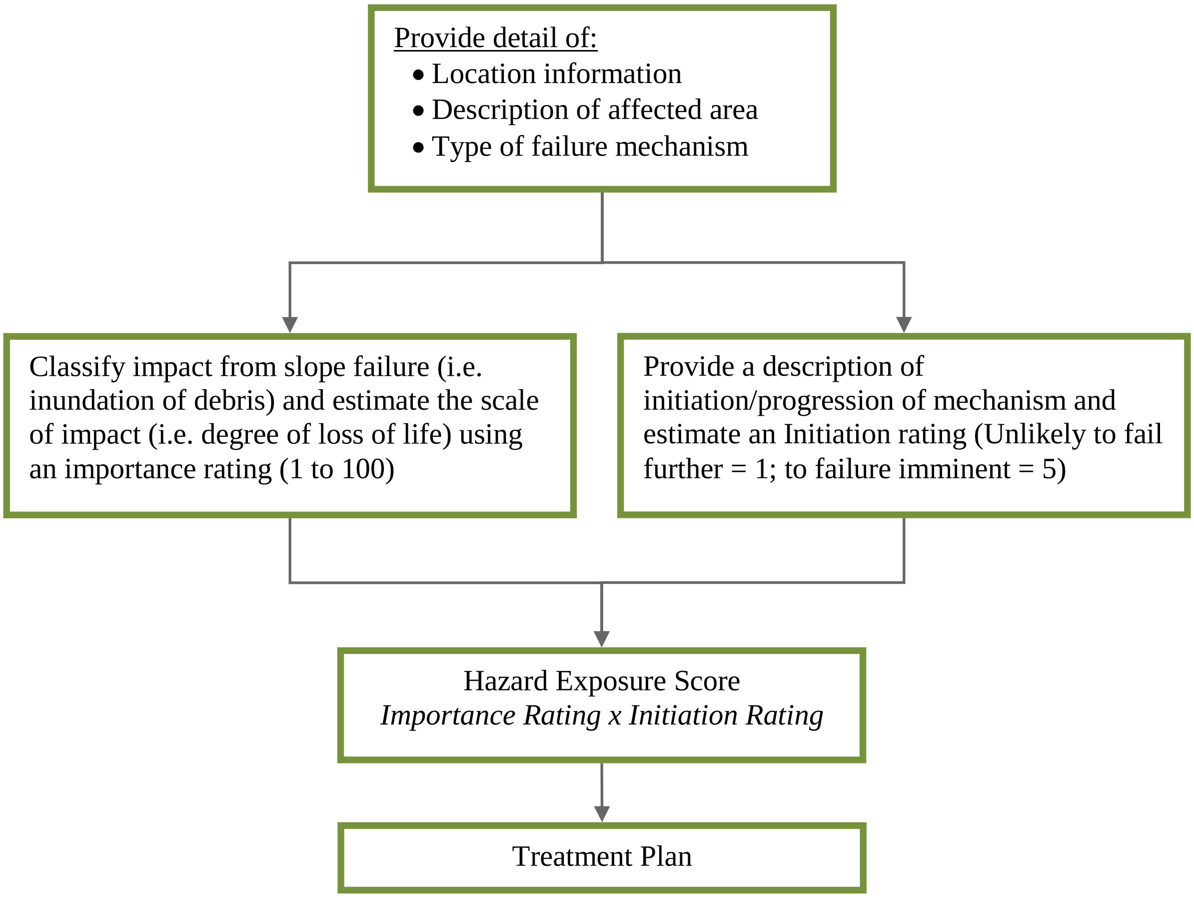


Figure 3.13: Format for slope assessment outlined by standard reporting format that was developed one week after the 22nd February 2011 earthquake

This assessment process appears to have followed a similar procedure to that of the landslide risk assessment outlined by Crozier and Glade (2004); Fell et al. (2005); and *AS/NZ ISO 31000:2009 Risk Management – Principles and Guidelines* where hazard analysis, consequence analysis, risk estimation, risk evaluation and risk treatment is encompassed in the management process (Figure 3.14).

Similarly to landslide risk assessment outlined by AGS (2000); Fell et al. (2005) (Chapter One) post-earthquake risk assessment for seismically induced slope failures is composed of hazard analysis and consequence analysis. Post-earthquake risk assessment is differentiated from the landslide risk assessment processes outlined by AGS (2000); Fell et al. (2005) by replacement of frequency analysis with the requirement for an estimation of the likelihood of further failure and the failure timeframe. Both estimations are informed through the characterisation of slope failures based on rapid observations made onsite. Post-earthquake consequence analysis encompasses rapid estimation of the exposure of residents to further slope failure and thus analysing the life safety impact.

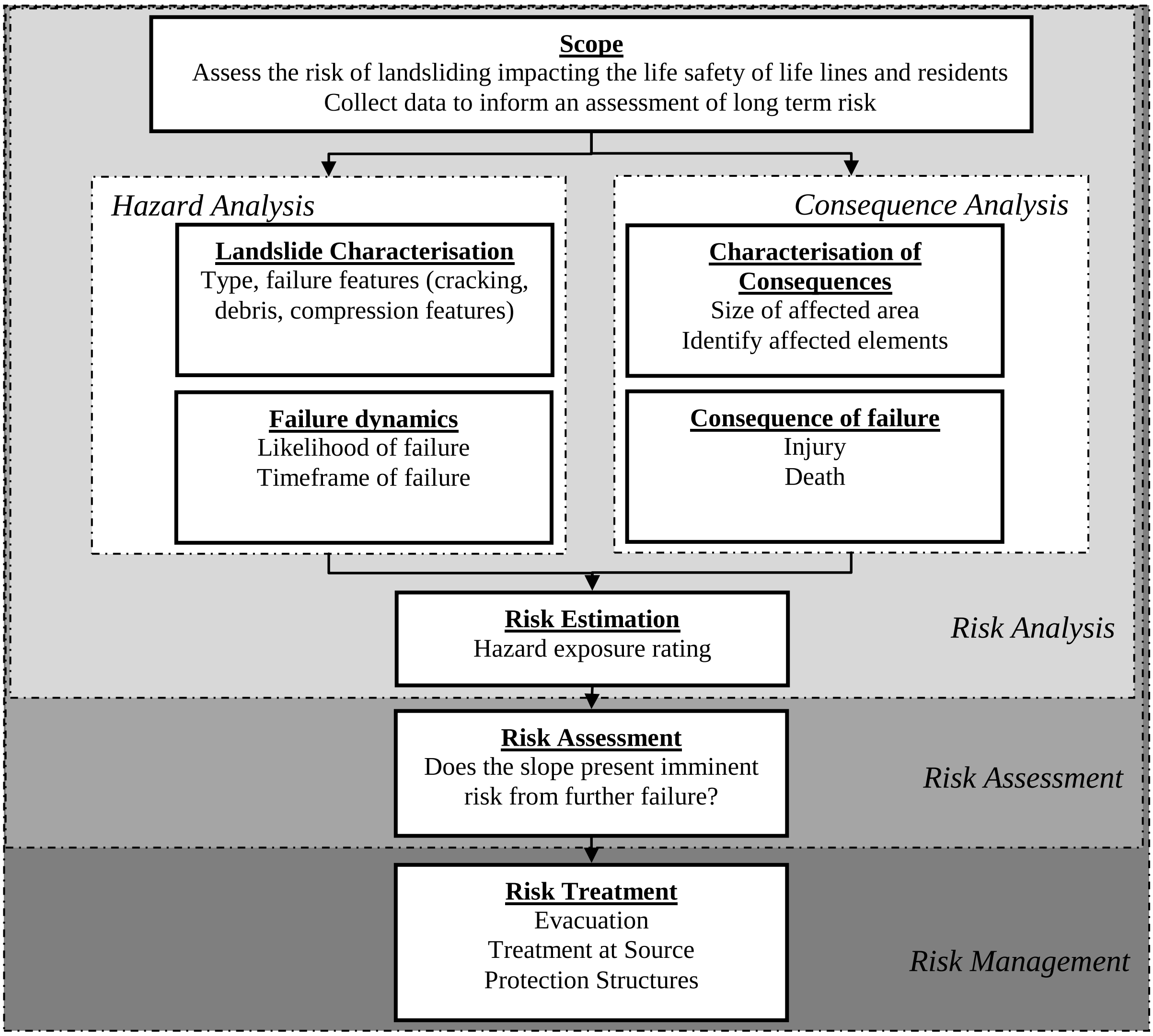


Figure 3.14: Interpretation of the process for post-earthquake risk assessment of earthquake-induced landsliding implemented during the response to the 22nd February 2011 earthquake, approximately one week post-earthquake

Due to the implications of imminent risk on the life safety of residents there was little time for detailed assessment to calculate the vulnerability of elements at risk as part of the consequence analysis. In the absence of this, an approximation of the population exposed to the hazard in question was made and qualitative numerical measures were used to generate a hazard exposure score to quantify the level of risk at the site (Appendix G). In the case of rapid emergency risk assessment of earthquake-induced slope failures, the process of generating a hazard exposure scope is useful in maintaining consistency within slope assessments and follows typical risk management procedures.

It is unclear to what extent the slope assessment reporting format was implemented throughout the group and issues arose when geotechnical professionals collected varying levels of detail which made data collation difficult. The collection of null data was important so that geotechnical professionals were not deployed multiple times to areas that had already been assessed and no hazard found. The assessment process outlined in the slope assessment reporting format was structured around the evaluation of the slope failure feature and how it impacts vulnerable elements, rather than how slope failures impacted a particular dwelling. While this process was ongoing, geotechnical professionals were also assessing the effect of slope failures on particular dwellings by responding to call outs from CDEM and USAR.

From March 2011, field assessment of rockfall began to include evaluation of boulder stability to classify the associated risk level (Macfarlane and Yetton 2013). An assessment criteria was developed to include rock size and shape, evidence of recent movement and property or lifelines at risk to classify whether the unstable rocks were high, medium or low risk. Field stability classification for rocks and boulders based on the following criteria (Macfarlane and Yetton 2013):

1. Individual rock or boulder is detached – either loose boulders or in outcrop where fresh cracking is present above/below individual rock or within rock mass.
2. Ability to roll – examine rock shape.
3. Would the release of boulder or rock result in threat to properties or lifelines?
4. Is rock unstable at time of assessment (moves when pushed by hand).

One to two months after the earthquake PHGG began to focus on collecting data to inform a detailed life safety risk model developed by GNS Science, which aimed to quantify the Annual Individual Fatality Risk in the Port Hills from cliff collapse and rockfall. Annual Individual Fatality Risk refers to the probability (likelihood) that a particular individual will be killed in any year at their place of residence as a result of rockfall or cliff collapse (Massey et al. 2012a; Massey et al. 2012b). Geotechnical professionals were primarily involved in the mapping of boulders and cracks to provide data for the hazard model that was beginning to be developed by GNS. The aim of the detailed life safety risk model was to formalise the initial assessments of risk to life safety to remove the element of expert opinion, and to include physical measurements which would reduce the uncertainty included in the emergency response slope assessments.

3.4.2.3 Slope assessment after the State of National Emergency ceased

Reassessment of risk to life safety continued throughout the response period in an effort to periodically re-evaluate the requirement for building safety evaluation notices on dwellings.

At the end of the state of national emergency (30th April 2011) the building safety evaluation notices that had been assigned by the Civil Defence building safety evaluation teams were to be replaced by the section 124 (s124) notices under the Building Act, 2004 (Macfarlane and Yetton 2013). The method of assessment of S124 notices was primarily hazard characterisation which was less dependent on calculated risk and numerical values relating to the consequence of failure and the likelihood of failure. The S124 notice hazard analysis methodology enabled the interaction between hazard characteristics and environmental factors to assist decisions regarding safety around the slope failure and was more simplistic then the standard risk assessment format used during the state of national emergency.

S124 notice assessment flow charts were developed for each failure mechanism to ensure that the decision making process was kept systematic and consistent to ensure that geotechnical professionals undertaking the assessments would arrive at a rational conclusion. The s124 notice flow chart for boulder roll is attached in Appendix H. Assessments were undertaken by two or three geotechnical professionals, one of which was required to be a senior geotechnical professional. This flow chart system was informally accepted by the Christchurch City Council.

After the 13th June earthquakes, the Port Hills Geotechnical Group reassessed slopes within their sectors. Sectors located around the Sumner areas were affected the worst by the earthquake, and entire slopes within these sectors were required to be reassessed. S124 notices that had been assigned to houses were checked, and in some cases further s124 notices were assigned to houses that had previously been unaffected by the earthquakes.

3.4.2.4 Protection of life safety

Immediately after the 22nd February earthquake the following techniques were used in the Port Hills for the protection of life safety:

- Evacuation
- Enforcement of Building Safety Evaluation Notices (building use restrictions)
- Road closures
- Road use restrictions

Also implemented after 4th September 2010

One week after the earthquake emphasis was beginning to grow on the stabilisation of rock bluffs above roads and lifelines in particular to reduce the life safety risk posed to road users.

At this stage stabilisation work was also undertaken above undamaged houses to prevent further damage from rockfall. Consultancies involved in the geotechnical response partnered with local contractors to undertake mitigation and remedial works within each sector. Evacuations and enforcement of building safety evaluation notices were completed several weeks after the earthquake. In the days after the earthquake, it was unclear how temporal changes in the requirements and priorities of the geotechnical response would progress. Initially, geotechnical professionals expected most residents to be returned to their homes in the Port Hills months after the earthquake, however, over time it became apparent that the earthquake had affected the long-term stability of the slopes in the Port Hills.

The approach to the protection of life safety in the Port Hills changed after the 13th June 2011 earthquake, when it was decided that treatment at source areas alone was no longer solely sufficient to decrease the risk to life safety from earthquake-induced slope failure. Slopes that had been classed as low or medium risk after the 22nd February 2011 event had released material subsequent to the 13th June earthquake, indicating the complexity in assessing the behaviour of the Port Hills considering the high peak ground accelerations produced by close-proximity faulting. Until the 13th June 2011 earthquake, geotechnical professionals expected that with slope stabilisation and remediation work most residents would eventually re-occupy their homes. After the 13th June 2011 earthquake, CCC shifted from aiming to make homes in the Port Hills re-inhabitable to primarily focusing on lifeline and infrastructure protection. Area-wide rockfall protection was considered in detail by the CCC, but due to the cost and extent of protection required this was deemed not feasible as a single solution in June 2012. During this time CCC and CERA decided that avoidance would be the preferred options for residential dwellings in the Port Hills.

3.4.3 Public communication

Public communication was identified as a crucial theme in the geotechnical response throughout the Canterbury Earthquake Sequence. Because of the life safety risk posed by slope failures it was imperative that the public was made aware of the situation in the Port Hills. After the 4th September 2010 earthquake public communication regarding clean up of rockfall in the Port Hills was maintained through publication of information in newsletters, and on the Christchurch City Council (CCC) website. After the 22nd February 2011 earthquake the large extent of residential area affected by coseismic slope failure meant that public demand for information was significant, however, it took some weeks to coordinate communication with residents appropriately. Table 3.15 summarises the progression of changes within public communication after the 22nd February 2011 earthquake.

Table 3.15: Changes in public communication during the response to the 22nd February 2011 earthquake

Timeframe	Method of public communication
Immediately post-earthquake	• Individual Communication between geotechnical professionals, USAR and residents
Second week post-earthquake	• CCC and CDEM started to organise community meetings in the Port Hills • Community meetings are attended by representatives from the PHGG, USAR, CDEM and the mayor of Christchurch. • Representatives from PHGG explain to residents what impact the earthquake had on the Port Hills and what risks were associated with the slope failures.
From second week post-earthquake	• Port Hills Geotechnical email address established to update residents • During community meetings CDEM science liaison gathered email addresses of residents in the Port Hills • Management of the email address was initially overseen by CDEM Science liaison, and later CCC. Involvement of CCC took some time as there was an exhaustive need for communication within the response which overloaded their communication resources. • Fact sheets were developed by CDEM Science liaison from approximately one week post-earthquake to provide information regarding tsunami risk, earthquake risk, road closures, and the building safety evaluation process. • Fact sheets were uploaded to the Christchurch Earthquake Response Centre website and were distributed by hand to resource centres in suburbs throughout Christchurch. • From days after the earthquake residents contacted the CCC and CDEM Call Centres to seek information • Information gathered from call centre regarding slope failure locations became influential in the deployment of geotechnical professionals

Although the demand for information from residents was high, residents were also a useful source of information concerning the location of slope failures within neighbourhoods. This influenced the deployment of geotechnical professionals. Public communication became a large constituent of the response from the PHGG, and over time the methods for public communication increased from individual communication to community meetings. Approximately one week after the earthquake it started to become apparent that the residents were finding it difficult to discern when a Building Safety Evaluation notice had been placed on a house for structural reasons or geotechnical reasons as the existing system did not accommodate this distinction. Civil Defence and Emergency Management (CDEM) Science liaison personnel from the emergency response centre noticed that there was a lack of detailed information regarding which houses had been deemed unsafe due to geotechnical reasons. This made it difficult to inform residents whether their houses were structurally unsafe or exposed to risk posed from earthquake-induced slope failures.

For a period of time after the implementation of the Canterbury Earthquake Recovery Act (2011) community meetings in the Port Hills were deferred until further notice while strategic level organisations defined their roles and focussed on co-ordinating systems to facilitate consistency in public communication. Consequently it became difficult at times for residents to obtain the information.

3.4.4 Accessibility and Liability

Accessibility and liability were two elements of the response which were indentified intermittently throughout the interviews regarding the geotechnical response to the 22nd February 2011 earthquake. These themes were less significant as they had a minor impact on the progression of the response. Examples of when accessibility and liability influenced the geotechnical response include:

Accessibility

- Immediately after the 22nd February 2011 earthquake, several geotechnical professionals were unable to access areas of the Port Hills due to damage to infrastructure and slope failure debris blocking roads. In the immediate aftermath of the earthquake this made the execution of slope assessments difficult in some areas until debris could be removed.
- Immediately after the 22nd February 2011 earthquake, the local CDEM Emergency operations Centre (EoC), which was located at the Christchurch Art Gallery in the Central Business District, was easily accessible as the cordon in the central city was still forming. Geotechnical professionals could easily access the response centre

without requiring formalised access documentation. Days after the earthquake, as management of the cordon improved, geotechnical professionals were unable to gain access to the response centre. Consequently meetings for the geotechnical response group were relocated from the CDEM response centre to Opus International Consultants.

Liability

- Throughout the majority of the response, liability was addressed through contractual agreements between geotechnical professionals and CCC. Liability became a concern for some geotechnical professionals after the 22nd February 2011 earthquake that did not have the required insurance or contractual arrangement to limit their legal obligations if their involvement in the geotechnical response resulted in further loss. Once this issue was identified, protection from liability was provided to geotechnical professionals who did not have pre-existing liability cover.

3.5 Summary

The response to earthquake-induced slope failure in the Port Hills during the Canterbury Earthquake Sequence was an evolutionary process that has been the product of changing response priorities and requirements, and the lack of pre-existing systems to inform a geotechnical response. The objectives, themes and activities of the geotechnical response were adapted and modified with the occurrence of major earthquakes such as the 4th September 2010, 22nd February and 13th June 2011 earthquakes.

Ground motions and slope failure experienced in the Port Hills after the 22nd February 2011 earthquake was unprecedented and did not conform to historical evidence of slope failure in the Port Hills, or the seismic hazard model for Christchurch. Ground motions experienced in the Port Hills during the 22nd February 2011 earthquake significantly exceeded the New Zealand standard 500-year seismic design spectra. Consequently, planning and preparation for response to widespread slope failure was insubstantial and it took several weeks after the 22nd February 2011 earthquake for a coordinated geotechnical response to develop.

Development in response coordination became important in the aftermath of the 22nd February 2011 earthquake increase efficiency of slope assessment and enforcement of evacuations during the emergency response. Imminent risk from slope failures was addressed through evacuations, building use restrictions and road use restrictions. Protection of life safety, lifelines and the continuation of public communication remained important in the response from days to years after the 22nd February and 13th June 2011 earthquakes.

Chapter Four: Historical and international earthquake case studies

4.1 Introduction

The purpose of this chapter is to present a review of literature detailing post-earthquake response to coseismic slope failure during the 2008 Wenchuan, China, earthquake; 1999 Northridge, California, earthquake; and 1994 Chi-Chi, Taiwan, earthquake. Review of historical, international earthquakes has provided insight into response techniques, priorities, and requirements that have previously been implemented during management of life safety risk associated with earthquake-induced slope failure. Response techniques from historical earthquakes can be used to develop a framework for geotechnical response to landslides induced by earthquakes, which can inform comparison with the geotechnical response to the Canterbury Earthquake Sequence. Lessons learnt from past events have been used to develop methods for future response to earthquake-induced landslides, and are presented in subsequent chapters.

4.2 The 1994 Northridge, California Earthquake

On the 17th January 1994 a M_w 6.7 earthquake struck California. The earthquake hypocentre was located 18km beneath Northridge city on a blind thrust fault in the San Fernando Valley (Parise and Jibson 2000). The area in which the earthquake struck is regarded as one of the most prepared and best engineered metropolitan areas in the United States (Norton et al. 1994). Despite this, the earthquake caused the loss of 57 lives, and injured a further 9,000 people (USGS 1996). The earthquake destroyed and damaged infrastructure such as buildings, main transportation routes, and gas lines. After rapid building inspection at least 1,600 buildings were deemed unsafe with a further 7,300 buildings restricted to limited entry.

4.2.1 Overview of earthquake-induced landslides

Coseismic landsliding was widespread throughout the San Fernando Valley. At the northwest end of the valley ground failure was the principal cause of destruction (Parise and Jibson 2000). In general, damage from landslides induced by the 1994 Northridge earthquake was only described as moderate because the areas of greatest landslide activity were sparsely populated (Harp and Jibson 1996). Figure 4.1 shows the extent of landsliding that occurred relative to the earthquake epicentre.

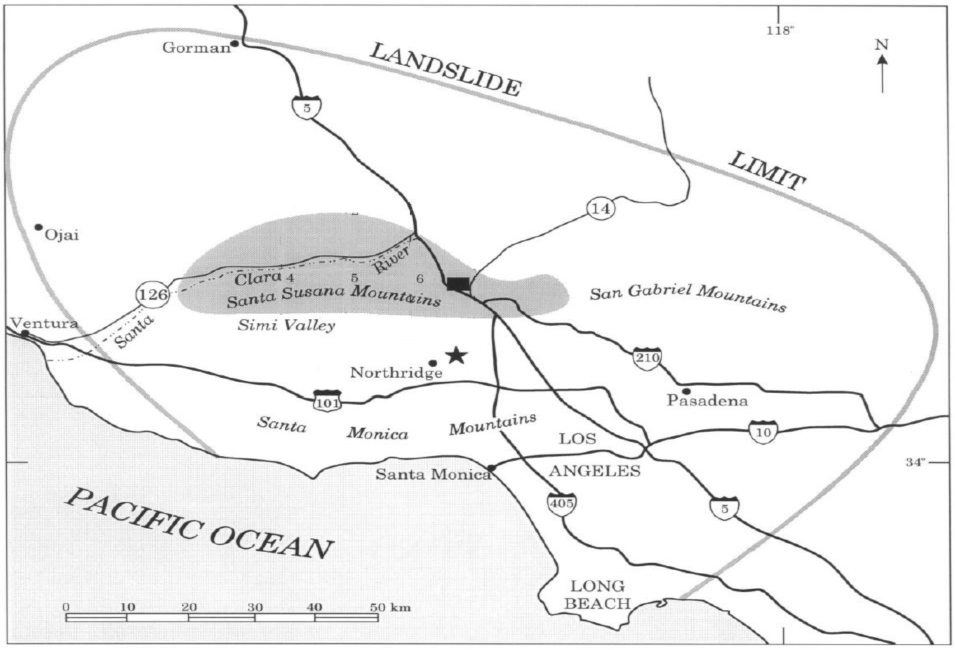


Figure 4.1: Location of 1994 Northridge earthquake, California and the extent of earthquake-induced landslides (Harp and Jibson 1996).

Coseismic landsliding included the following types (Parise and Jibson 1997):

- Highly disrupted shallow falls and slides in rock and debris which were the most common type of landslide.
- Coherent slumps and block slides which were less numerous compared to highly disrupted shallow falls and slides.

Some residential dwellings in central and eastern Santa Monica were moderately to severely damaged from reactivated deep block slides. Rockfall damaged and destroyed some non residential buildings in the Santa Susana Mountains. Fill failures and shallow, disrupted slides were also responsible for damaging buildings (Harp and Jibson 1996). Many pipelines and lifelines were damaged by rockfalls, slumps and block slides which either inundated services with debris, or undermined services (Harp and Jibson 1996).

4.2.2 Geotechnical response to earthquake-induced landslides

The progress of response to earthquake-induced landslides has been detailed in Table 4.1. Existing response capabilities within the United State Geological Survey (USGS) ensured that geotechnical experts were rapidly deployed hours after the earthquake to address the geotechnical hazards associated with the earthquake (USGS 1996). Procedures were in place for geotechnical assessment in relation to building safety evaluation; these were outlined by the guidelines *ATC-20 Procedures for Post-Earthquake Building Safety Evaluation* that had been developed prior to the Northridge earthquake (see Appendix I).

Although the ATC-20 guidelines primarily detail procedures for structural assessment of earthquake-damaged buildings, emphasis is also placed on the inspection of geotechnical hazards that may compromise the structural capability of a dwelling or present a life safety risk. Response to geotechnical hazards detailed in ATC-20 includes:

- Assessment of surface fault rupture with respect to:
    - Damage to buildings from ground displacement
- Assessment of slope failures with respect to:
    - Foundation damage or loss of foundation support
    - Continuing slope movement under static conditions
    - Buildings in active slope failure zone
    - Building in path of falling debris or rock
    - Retaining wall leaning outward of 5° or more to vertical
- Assessment of 'Other' differential ground movements with respect to:
    - Ground fissures and scarps > 4 inches wide near buildings
    - Buildings damaged by ground displacement (vertical or horizontal)
- Assessment of earth dam or reservoir movement with respect to:
    - Cracks, increased seepage, or embankment failure of earth dams
    - Overtopping of dam by wave

Appendix I presents section 11 of the ATC-20 guidelines which detail the procedures for post-earthquake inspection of geotechnical hazards and recommended actions for inspection of the hazards listed above. The guidelines highlight the requirement for expert judgement during assessment, and inform on the appropriate professionals qualifications and experience required for assessors involved in the geotechnical response. The utilisation ATC-20 guidelines after the 1994 Northridge earthquake suggests that there was no requirement for a response methodology to be developed post-earthquake. Furthermore, use of the ATC-20 guidelines ensured that consistency within management of slope failures could be maintained through implementation of recommended actions provided.

Table 4.1: Response to earthquake-induced landsliding after the 1994 Northridge earthquake

Time after earthquake	Response to Landslides
Hours	• Aerial photography was undertaken by the United State Air force hours after the earthquake. These photographs were to a scale of approximately 1:60,000 and were used by scientists to create a post-earthquake landslide inventory (Harp and Jibson 1995). Although some of the smaller landslides were not able to be captured in the imagery, the photographs enabled identification of areas affected by larger landslides (Harp and Jibson 1995). • Scientists from USGS deployed to investigate the geological and engineering effects of the earthquake (USGS 1996)
Days to weeks	• Field investigations included general site inspections and also geophysical and geological investigations (USGS 1996). • Scientists drove out from the epicentral area of the earthquake until only small failures of minor rock or soil mass had been obviously dislodged. Up to 90% of the area was mapped for landslides which enabled a landslide inventory to be developed (Harp and Jibson 1995). • Debris clearing commenced, removal of rock from some roadways took several months (Harp and Jibson 1995). • Seismic instruments were deployed by a team of experts from universities, private companies and USGS. Approximately 80 Instruments were installed and relocated as needed to measure seismicity ground deformation (USGS 1996). Information was used to produce GIS-based maps which showed areas of potential ground failure, shaking levels and local site amplification. • Data availability was a priority in the aftermath so that the public could be kept informed of hazards, and consequently collected data was distributed using the internet, fact sheets and magazines (USGS 1996).

Time after earthquake	Response to Landslides
Weeks to Months	• The landslide inventory has become a tool for creating landslide susceptibly maps and seismic hazard maps for the area (Jibson et al. 2000). Several forms of susceptibility maps have been developed since the earthquake. Geological data for the maps is typically sourced from county geologists, private consulting firms and the California Division of Mines and Geology (USGS 1996; Jibson et al. 2000). The intention of these maps is to provide emergency planners, infrastructure owners, and the public with an overview of where landslides are more likely to occur (Jibson et al. 2000) • GPS measurements of regional ground deformation were collected weeks after the earthquake (Parise and Jibson 2000).
Months to Years	• Analysis was undertaken to determine the susceptibility of geological units to landsliding. This was possible after the Northridge earthquake because of existing geological mapping, and because of the thorough mapping of landslides location and geometry in the area. The analysis assigns each geological unit with a landsliding susceptibility rating (Parise and Jibson 2000). • Seismic hazard assessments for the area were updated to include new faults recognised as a result of the earthquake, and update estimated levels of ground shaking for future events. Updating seismic hazard maps primarily affected household or property insurance rates, recommended building design standards and refined allocation of Federal Emergency Management Agency (FEMA) assistance funding (USGS 1996). • In 2011, the Californian Geological Survey produced a map showing the susceptibility of deep-seated landslides in California. This map considers estimates of the level of rock mass strength and slope steepness to generate the susceptibility to deep-seated landslides (Wills et al. 2011). Research has also been undertaken to quantify the susceptibility of geologic units in the Los Angeles area based on the characteristics of the landslides induced by the Northridge earthquake (Parise and Jibson 2000).

4.2.3 Priorities during the geotechnical response

The timeline of response activities in Table 4.1 provides insight into the progression of priorities throughout the geotechnical response to earthquake-induced slope failure. In the immediate aftermath of the Northridge earthquake the initial priorities regarding the management of earthquake-induced slope failure included the following:

- Execution of an impact assessment to identify the extent of slope failure,
- Improvement of accessibility where infrastructure has been impacted by slope instabilities,
- Protection of life safety through the implementation of building safety evaluation under the ATC-20 guidelines (Applied Technology Council 1995).

From days after the earthquake, scientists were involved in data collection to inform the analysis of landslide susceptibility and the review of landslide hazard maps months post-earthquake. It is likely that the occurrence of slope instabilities in less populated areas resulted in less requirement for protection of life safety from earthquake-induced slope failure. Reviewed literature in Table 4.1 suggests that transition of the response priority to assessment of long term risk associated with earthquake-induced landslide hazards took place weeks after the earthquake. Months after the earthquake the primary focus in the geotechnical response to Northridge was on improving scientific understanding of landslide hazard and risk subsequent to analysis of slopes affected by the earthquake.

4.2.4 Challenges within the geotechnical response

The impact of earthquake-induced landslides in the 1994 Northridge earthquake affected the response. Challenges in the geotechnical response were primarily related to accessibility. Earthquake-induced landsliding caused disruption to roadways which hindered relief efforts and exacerbated transportation problems. In some cases rockfall and rock slides closed alternate access routes, and it was several days before routes were cleared of debris (Harp and Jibson 1996).

California was subject to a number of disasters and emergencies prior to the 1994 Northridge earthquake, and consequently emphasis had been placed on preparedness and response planning prior to the earthquake occurring (Norton et al. 1994). Overall, the response to the

1994 Northridge experienced few coordination concerns; one primary disruption to the response was temporary loss of computer systems in the City Police Department communication centre, and the malfunction of generators immediately post-earthquake (Norton et al. 1994).

Engineering response to building safety evaluation in both structural and geotechnical assessments was strained in the assessment and management of damage to wood-frame dwellings. Inconsistent structural assessments and poor communication between engineers and clients was the product of a shortage of experienced engineers, and a lack of guidelines to inform building assessment, investigation and repair of buildings (Osteraas et al. 2000). This identified the need for further review of the execution of building safety evaluation post-earthquake, despite the existence of guidelines.

4.3 The 1999 Chi-Chi, Taiwan Earthquake

On the 21st September 1999 a M_W 7.6 earthquake struck the central region of Taiwan near the town Chi-Chi (Figure 4.2). Rupture of the Chelungpu fault caused a surface rupture that extended for 105km with the greatest recorded vertical displacement of 11m (Loh and Tsay 2001). The fault plane is nearly north-south trending and dips approximately 30° east (Shin and Teng 2001).

The extensive surface rupture and large magnitude of the earthquake caused widespread damage in the western region of Taiwan which was previously considered less seismically active than the eastern region (Dong et al. 2000; Shin and Teng 2001). Approximately 2,470 lives were lost during the earthquake, and a further 11,305 were injured, and at least 100,000 structures were destroyed (Goltz et al. 2001; Shin and Teng 2001; Lin and Tung 2004). Approximately 10,000 landslides were induced by the earthquake, most of which occurred on the east side of the Chelungpu Fault (Sitar et al. 2001).

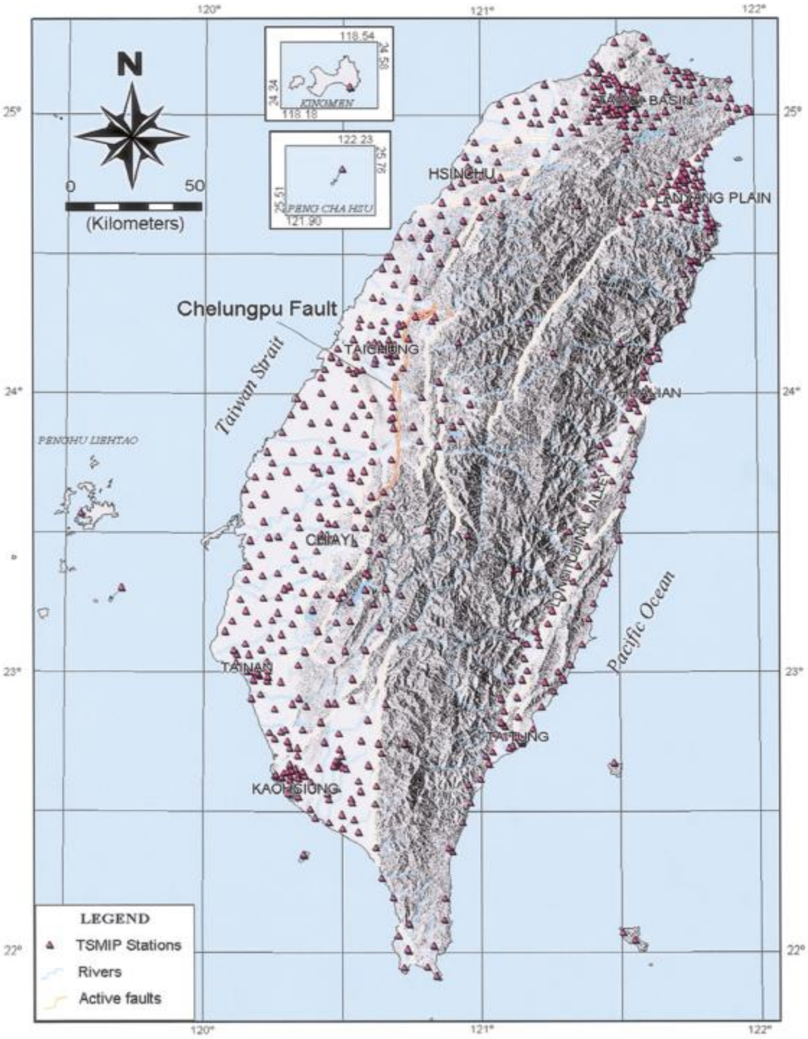


Figure 4.2: Location of 1999 Chi-Chi, Taiwan earthquake (Shin and Teng 2001)

4.3.1 Overview of earthquake-induced landslides

Earthquake-induced landslides caused the greatest loss to agriculture and tourism sectors in Taiwan, however, roads and infrastructure were also significantly damaged (Goltz et al. 2001). Shallow failures caused the majority of landslide-related damage, and typically threatened mountain roads and structures located at the base of slopes (Sitar et al. 2001).

Coseismic landsliding included the following types (Hung 2000; Sitar et al. 2001):

- Shallow slides on steep slopes in stiff soils and jointed rock;
- Rockfall;
- Deep seated failures;

- Very large catastrophic landslides, which appear to refer to slope failures with uncategorised failure mechanisms.

Following the Chi-Chi earthquake one of the main geotechnical concerns was the development of landslide dams from debris blocking stream flow, and increased susceptibility of further slope failure post-earthquake (Hung 2000). The risk from landslide dams can often be significant because of the susceptibility of the debris embankments to over-topping from high rainfalls. Embankment materials can also become mobilised following rainfall, causing instability issues in the dam.

4.3.2 General emergency response

Hours after the Chi-Chi earthquake struck, government officials assembled at the National Fire Headquarters to commence the initiation of the response and communicate with local agencies. On the 25th September, the National Government declared a six month State of Emergency for Taiwan to facilitate the emergency response and recovery in the nation (Goltz et al. 2001). Search and rescue commenced immediately after the event. Initially this was undertaken by residents and communities, however hours after the event organised search and rescue teams and trained volunteers responded. The response was enlarged by the mobilisation of armed forces to assist with the search and rescue and body recovery, and within 24 hours after the main earthquake international search and rescue teams were deployed to areas within Taiwan (Goltz et al. 2001).

Building safety evaluations were undertaken using a similar system to the Californian Applied Technology Council "ATC-20 *Procedures for Post-Earthquake Safety Evaluation of Buildings"*, where buildings were assigned entry restrictions according to the degree of damage to the structure (Goltz et al. 2001). Later in the response, building damage data was fed to the data management centre and compared with fault rupture location to provide analysis of earthquake impact (Loh and Tsay 2001).

4.3.3 Geotechnical response to earthquake-induced landslides

The organisation of the geotechnical response to the Chi-Chi earthquake was derived from hazard mitigation strategies that have been developed in Taiwan over the past 30 years. In

1982 the National Science Council of Taiwan (NSC) launched a series of research programs to improve hazard mitigation, pre-disaster preparedness, and emergency response in Taiwan (Loh and Tsay 2001). Development in the research enabled response methodologies to be established which involved the following Taiwanese agencies: National Centre for Research on Earthquake Engineering (NCREE), the Office of the National Science and Technology Program for Hazards Mitigation (NAPHM) and NSC (Loh and Tsay 2001; Lin 2006). Days after the Chi-Chi earthquake reconnaissance teams were organised by the NSC, while NAPHM and NCREE provided technical support and data management. Figure 4.3 shows the framework for management of reconnaissance teams in response to the Chi-Chi earthquake. This framework presents a system for analysing the components of an earthquake event and outlines which organisations are responsible for aspects of the response.

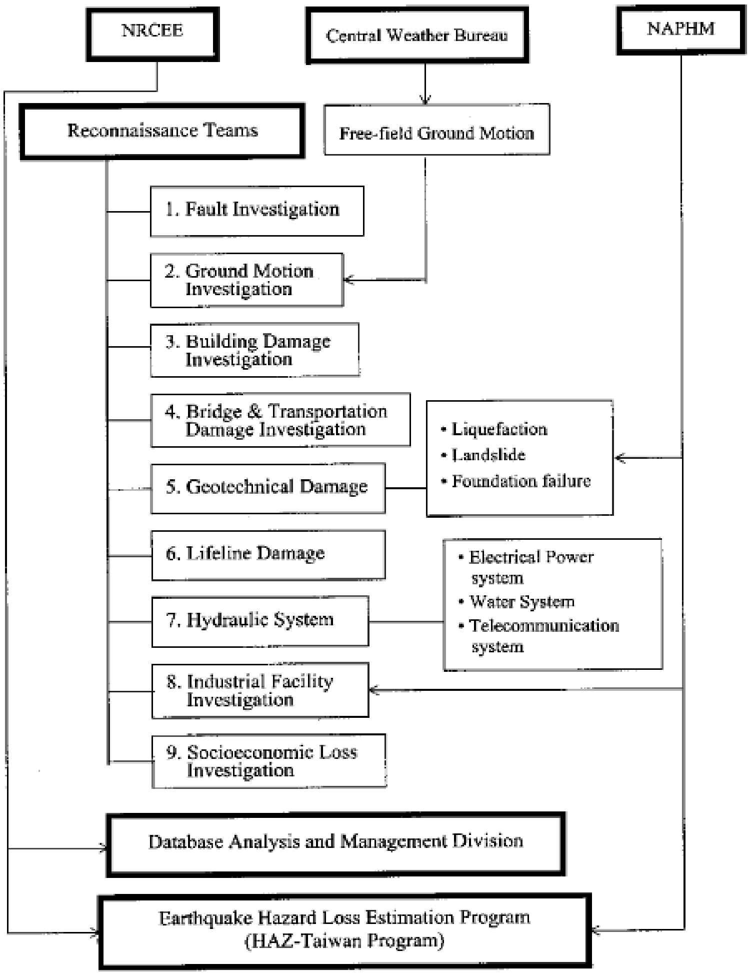


Figure 4.3: Framework for earthquake response (Loh and Tsay 2001)

Before the earthquake struck, NAPHM had set up a GIS-based map for each county in Taiwan which allowed the timely integration of data collected during ground reconnaissance to produce reports on the earthquake impact across Taiwan. Immediately after the earthquake GIS proved to be an asset in assisting emergency recovery and response teams making decisions (Loh and Tsay 2001). Spatial damage data analysis also helped identify areas worst hit by the earthquake and in most need of assistance (Loh and Tsay 2001; Lin 2006). Ground motion data integrated with the GPS coordinates of the fault location assisted the analysis of ground motion attenuation (Loh and Tsay 2001; Lin 2006). Table 4.2 details the response to earthquake-induced landslides after the Chi-Chi earthquake.

Table 4.2: Response to earthquake-induced landslides after the 1999 Chi-Chi, Taiwan earthquake

Time after earthquake	Response to Landslides
Days to weeks	• Aerial photographs and satellite images taken days after the earthquake were used by government agencies to locate landslides (Lin 2006). • NSC mobilised reconnaissance teams days after the earthquake event to assess damage and collect scientific data (Loh and Tsay 2001; Lin 2006). Teams were composed mainly of professors and graduate students from universities (Hung 2000). >1,200 scientists and engineers were required to conduct systematic field surveys to collect scientific data to analyse the effect of the earthquake (Loh and Tsay 2001). Each team developed an investigation format with the intention of incorporating the information into electronic databases (Loh and Tsay 2001). The NCREE provided technical support and the NAPHM provided information and assisted with data management (Loh and Tsay 2001). • Emergency spillways were constructed in landslide dams to prevent overtopping. Analysis of each landslide dam's inundation potential was conducted immediately (Hung 2000). Analysis of upstream rainfall run off was incorporated in the analysis which allowed for a quantification of the risk that the dam created for people inhabiting areas downstream of the dam (Loh and Tsay 2001). • The fault rupture was mapped using GPS; this information was digitised into the GIS database to assist in earthquake analysis (Loh and Tsay 2001). • Once data had been collected it was uploaded to the Chi-Chi Earthquake Database Analysis and Management System (CEDAMS) GIS database for analysis. Information became accessible to the public, research institutes and investigation teams undertaking reconnaissance work (Loh and Tsay 2001; Khazai and Sitar 2004; Lin and Tung 2004).

Time after earthquake	Response to Landslides
Weeks to Months	• Landslide assessment took place in two phases, in Phase One landslide locations were identified using satellite and aerial imaging of the area. Initial field investigations took place to confirm site locations (Hung 2000). • The initial assessment led to Phase Two in January 2000, where larger landslides were identified from the aerial imaging, subsequent investigations of landslides were undertaken to appreciate the mechanics of the site, slope stability and risk of failure. Further investigation was funded by NCREE and NAPHM (Hung 2000).
Months to Years	• In the years following the Chi-Chi earthquake a preliminary GIS-based analysis of landslide susceptibility was undertaken using the information collected by the reconnaissance teams. The aim of the analysis was to build a predictive model for landslide occurrence given a similar future earthquake in the same area (Lin and Tung 2004). • As a result of the earthquake, Taiwan re-evaluated the seismic design code for buildings immediately after the event. A seismic hazard analysis was also undertaken to appreciate the Chelungpu fault which previously was considered one of the least active faults in Taiwan. The results of the Seismic Hazard Analysis were used to revise the seismic zoning of Taiwan (Loh and Tsay 2001). Initially before the earthquake Taiwan was divided into four seismic zones based on the expected peak ground acceleration that would be experienced from a 1 in 475 year seismic event. Timely completion of updates for the seismic hazard of Taiwan was important for recovery and reconstruction (Loh and Tsay 2001).

4.3.4 Priorities within geotechnical response

Activities during the geotechnical response to the 1999 Chi-Chi, Taiwan, earthquake provide insight into the priorities of the response. Similarly to the Northridge earthquake, the response to the Chi-Chi earthquake commenced with focus on conducting an initial impact assessment. Landslide dams were identified early in the response as high risk because of the consequences of further loss of life with dam-break. The emphasis on management of high risk coseismic hazards suggests that immediately after the earthquake one of the primary response priorities was the protection of life safety and quantification of the extent of impact post-earthquake. Throughout the geotechnical response to the Chi-Chi earthquake, emphasis was placed on timely data management. As such, early in the response Geographic Information Systems (GIS) databases became a predominant tool for data management and analysis to inform emergency response.

Similarly to the Northridge and Wenchuan earthquakes, over time (approximately months post-earthquake) detailed investigation of earthquake-induced landslides took place to inform analysis of landslide susceptibility in the earthquake affected area. Furthermore, revision of the seismic design code suggests that the response to the Chi-Chi earthquake transitioned to assessment of long term seismic and landslide hazards for reconstruction.

4.3.5 Challenges within the geotechnical response

The primary disruption related to response to earthquake-induced landsliding was the continuing impact of weakened slopes on infrastructure such as highways. Subsequent aftershocks and heavy rainfalls mobilised further down slope movement of material and resulted in further damage, loss of life and disruption to reconstruction (Hung 2000). In the immediate response (days after the earthquake) temporary roads were constructed to gain access to remote mountain regions which has been isolated by damage to roads and highways from earthquake-induced landslides (Dong et al. 2000).

The pre-earthquake research conducted to inform emergency response and pre-disaster preparedness guided the coordination of the geotechnical response to earthquake-induced landslides after the Chi-Chi earthquake (Loh and Tsay 2001). Reviewed literature has implied that further emergency response planning and preparation could be initiated to improve the future earthquake response, however, generally few deficiencies in emergency response coordination have been discussed. The use of GIS was considered a successful and important component of emergency management after the Chi-Chi because of the contribution that analysis and management of data through GIS provided to deployment and coordination of emergency relief to areas extensively impacted by the earthquake (Loh and Tsay 2001).

4.4 The 2008 Wenchuan Earthquake, Sichuan Province, China

On the 12th of May 2008 a M_w 7.9 earthquake occurred in the southern province of Sichuan, China (Huang and Fan 2013). The major shock was reported to have occurred on the Beichuan-Yingxiu fault, part of the Longmenshan fault zone (Cui et al. 2011). Aftershocks rapidly extended northeast-southeast along the Longmenshan fault located near the town of Wenchuan (Figure 4.4). The earthquake occurred in a densely populated mountainous region that has a history of frequent large magnitude earthquakes (Zifa 2008).

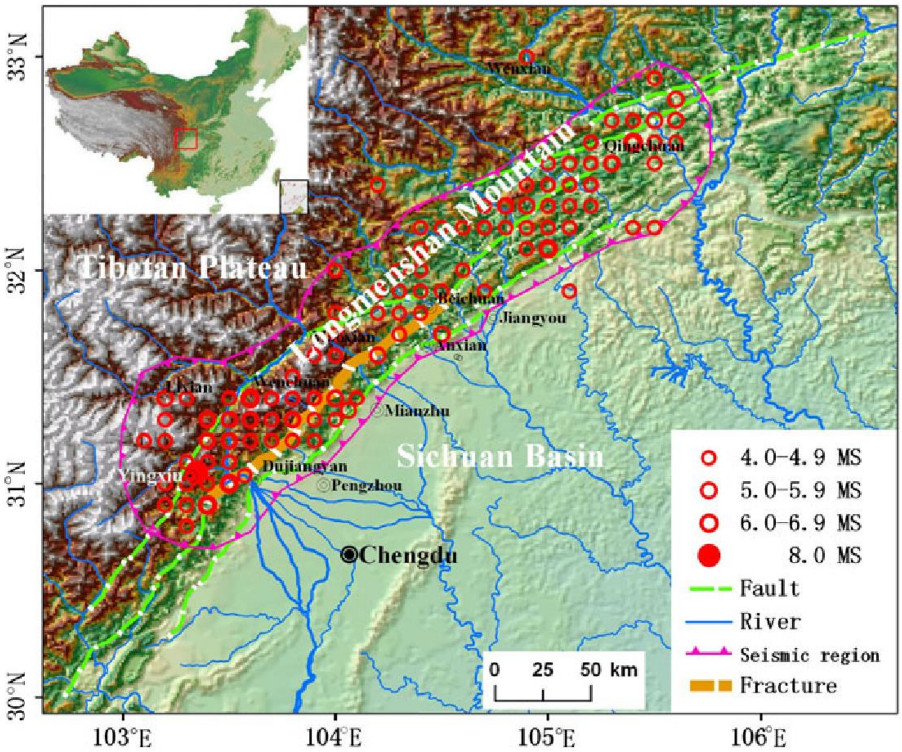


Figure 4.4: Location of the Wenchuan Earthquake and aftershocks (Cui et al. 2011)

At least 69,000 people died as a result of the earthquake and secondary earthquake-induced hazards (Brown et al. 2012). The earthquake also caused extensive damage to structures, infrastructure and dwellings. Typical buildings in the area had very low seismic resistance which resulted in extensive building collapse and damage (Zifa 2008). Many buildings were also damaged by slope failures induced by the earthquake, which contributed to the large number of deaths and injuries from the earthquake (Zifa 2008).

4.4.1 Overview of earthquake-induced landslides

Slope failure initiated by the 2008 Wenchuan earthquake caused damage to infrastructure, such as telecommunications, railways, bridges and electricity networks (Jian and Li 2011). Several major landslide dams formed where landslide debris blocked streams and rivers (Cui et al. 2009). Not only did the landslide dams flood dwellings and infrastructure upstream, the dams created a life-safety issue for many towns downstream (Cui et al. 2009).

Coseismic landsliding included the following types (Jian and Li 2011):

- Rockfall,
- Debris flow,
- Cliff collapse,
- Landslide, which appears to refer to large deep seated mass movements which does not directly conform to the definition of landslide in accordance with Cruden and Varnes (1996).

Many of the slope failure hazards occurred in historically active slopes or in areas where the rock mass was easily weakened (Jian and Li 2011). Ground motion and topographic amplification from the main earthquake and subsequent aftershocks created new fractures and joints which weakened the rock mass on many mountain slopes and peaks. This weakened the rock mass and increased the frequency of rockfall (Jian and Li 2011). Loosened slope materials and weakened rock masses reduced the stability of slopes and increased the susceptibility of further landsliding, particularly debris flows, in the area (Huang 2011).

4.4.2 General earthquake response and recovery

In the initial phases of the response, search and rescue was undertaken primarily by local community and neighbourhood groups (Earthquake Engineering Research Institute 2008). Within hours after the earthquake the China International Search and Rescue team and approximately 130, 000 soldiers from the People’s Liberation Army were rapidly mobilised for search and rescue purposes and to restore primary access routes between towns (Earthquake Engineering Research Institute 2008; Zifa 2008). Six response teams from the Institute of Engineering Mechanics and the China Earthquake Administration were also deployed days after the earthquake to assist with search and rescue, loss estimation, damage surveys, and structural safety evaluations (Zifa 2008). As the search and rescue phase progressed, distributing aid and providing the basic needs such as water, food, and housing to those affected by the earthquake became a more predominant activity in the response (Zifa 2008).

Several weeks after the earthquake, the response focus shifted from search and rescue to relief and reconstruction (Zifa 2008). China's State Council established an earthquake rescue and relief headquarters which developed strategic level goals every three months and focussed on recovery during the three years following the earthquake (Earthquake Engineering Research Institute 2008). Goals included the development of temporary housing, damage assessment, reconstruction planning, finance, and post-earthquake response management and implementation (Earthquake Engineering Research Institute 2008).

In June 2008 the Wenchuan Earthquake disaster Recovery and Reconstruction Act was passed by the State council to establish a multi-government management strategy. The new legislation enabled a post-earthquake assessment to commence to quantify the extent of damage and impact of the earthquake, including a thorough investigation of the impact of slope failures (Brown et al. 2012). In September 2008 the Chinese State Council issued a plan for urban development and reconstruction for 51 worst affected counties in Sichuan, Gansu and Shaanxi provinces (Brown et al. 2012).

The extensive damage and destruction of buildings also resulted in the need for reconsideration of the seismic design of buildings, particularly schools and hospitals (Zifa 2008). Ground motions experienced in the main earthquake were larger than design values suggested by the 2001 Chinese Seismic Code Zonation. This established the need for revision of this guideline to reduce risk from future earthquakes in the light of the rebuild process (Free et al. 2008; Zifa 2008).

4.4.3 Geotechnical response to earthquake-induced landslides

The response to coseismic landslides and landslide dams was an evolutionary process where the degree of detail in the analysis increased over time. Table 4.3 details the response activities which took place hours, days, weeks and months after the earthquake. Response to landslide dams was prioritised in the aftermath of the earthquake because dam break could cause further loss of life and inundation of dwellings downstream or cause inundation upstream of the dam if water level was to rise. One of the landslide dams that formed from the earthquake threatened Mianyang city, which had a population of 1.3 million at the time of the earthquake. The consequences of a potential dam break were significant, and as such, timely and affective emergency treatment of landslide dams was required to manage the risk of dam break (Zifa 2008). Engineering geology assessments of coseismic slope failure became crucial during proposals for relocation of towns impacted by secondary hazards such as rockfall and debris flow (Huang et al. 2009).

Table 4.3: Response to coseismic landslides and landslide dams in the aftermath of the 2008 Wenchuan, China earthquake

Time Post Earthquake	Response to earthquake-induced slope failures
Hours	• Rescue work and disaster relief was focussed on Wenchuan city until satellite imagery was obtained to conduct an impact assessment (Huang 2011).
Days to weeks	• Aerial Photography of area affected commenced three days post-earthquake (Tang et al. 2009; Huang 2011). • Field investigations of earthquake-induced landslides commenced "immediately" to inform regional emergency assessment of landslide susceptibility to inform placement of refugees and future reconstruction (Tang et al. 2009). • Remote sensing and aerial imaging was used to give an initial assessment of the amount of water retained in landslide dams and the size of the landslide dams, as some were inaccessible in the early stages after the earthquake due to slope failures compromising access routes (Cui et al. 2009). • Statistical methods were used to quantify the associated risk threshold for each dam site based on the dam height, structure and lake capacity (Cui et al. 2009). Assessment of dam sites was critical as the likelihood of a potential breech needed to be quantified to gain an understanding of the risk to towns downstream (Cui et al. 2009). • Monitoring of landslide dams commenced after seven days; by 25th May 2008, 12 of the 33 'high risk' dams had failed due to overtopping (Cui et al. 2009). • Emergency treatment was undertaken e.g. channels cut in the embankment to mitigate potential dam breech (Earthquake Engineering Research Institute 2008; Chen et al. 2010).

Time Post Earthquake	Response to earthquake-induced slope failures
Weeks to Months	• Engineering geological and geomorphological assessments were undertaken in severely damaged counties (Huang et al. 2009). Assessments aimed to examine the requirement for relocation of towns where existing sites were impractical for reconstruction (Huang et al. 2009). • Characteristics such as faulting, folding, rock mass condition and topography were considered in the site selection process. In addition to this the social and economic aspects of the site needed to be considered (Huang et al. 2009). • Long term slope monitoring equipment was installed at several landslide sites to gain information about the slope movements and assess the slope response to ongoing aftershocks (Wang et al. 2012).
Months to Years	• Susceptibility mapping was undertaken after a request from the Chinese government (Tang et al. 2009). • The development of susceptibility maps involved using 20m x 20m digital elevation models (DEM) and aerial photography taken days after the earthquake. Field investigations were undertaken where landslides were most densely populated which allowed the assessment of failure mechanisms and instability factors. With this information, areas which were highly susceptible to land sliding could be identified. For the Wenchuan earthquake, landslide susceptibility was derived from topography, tectonics, lithology and stream proximity (Tang et al. 2009).

4.4.4 Priorities during geotechnical response

The timeline of activities in Table 4.3 provides insight into a progression of priorities that occurred during the geotechnical response to earthquake-induced slope failure. Early in the response to the 2008 Wenchuan earthquake, the geotechnical response was focussed on immediate relief, protection of life safety from imminent risk, and conducting an impact assessment. Emergency management (treatment and monitoring) of landslide dams became imperative in the immediate aftermath of the earthquake (days to weeks post-earthquake) because of the scale of potential impact to the life safety of resident downstream in the event of a dam-break. Emphasis on the protection of life safety can also be seen in the emergency investigations of landslides to inform the placement of refugees.

Weeks to months after the earthquake, the focus of the response began to encompass detailed assessment of slope stability and development of susceptibility maps to inform the relocation of towns (Huang et al. 2009). As such, reviewed literature suggests that the priority of the geotechnical response shifted from management of imminent risk in the days to weeks after the response, to the management and assessment of life safety risk from long term exposure to slope instabilities. In some cases the increased susceptibility of slopes to fail post-earthquake caused further loss of life and damage to infrastructure (Free et al. 2008; Huang 2011; Cui et al. 2011). This was a continuing challenge in the management of slope failures, which in some cases led to hazard avoidance. An example of this is the Beichuan county town which was damaged by rockfall during the earthquake, over one year later further damage and loss of life occurred from a debris flow which buried parts of the town (Huang 2011). The relocation of the population inhabiting Beichuan town emphasised the applicability of hazard avoidance where implementation of engineering protection or mitigation is insufficient in protection of life safety.

4.4.5 Challenges within geotechnical response

During the response to the 2008 Wenchuan earthquake there were a series of challenges that hindered the timely execution of the response. Challenges which occurred during the response included the following:

- <u>Accessibility:</u> Many towns became isolated due to slope failures blocking access routes and interrupting transportation and communication, this hindered the search and rescue efforts and contributed to a large number of deaths and injuries from the earthquake (Zifa 2008; Shi et al. 2009; Huang 2011). The extensive blockage of roads and access routes hindered the relocation of people as it became difficult to transit to other areas (Zifa 2008).
- <u>Continuing slope instability:</u> The increased susceptibility of slope failures after the earthquake created challenges for post-earthquake response and reconstruction as materials became easily loosened by rainfall which caused further loss of life, damage to infrastructure and created access problems throughout the region (Free et al. 2008; Huang 2011; Cui et al. 2011).
- <u>Response coordination:</u> The scale of the event and the extent of area impacted by the earthquake hindered coordination of the response to the 2008 Wenchuan earthquake (Shi

et al. 2009; Huang 2011). Communication disruption in Chengdu (the largest city in the area affected) during the first 24 hours after the earthquake delayed the execution of immediate response tasks such as impact assessment and disaster relief (Shi et al. 2009; Huang 2011). Although government departments in China were equipped with emergency response plans, the extent of disruption to infrastructure severely compromised the coordination between government agencies, which hindered the coordination of relief work and management of secondary hazards such as landslide dams (Earthquake Engineering Research Institute 2008; Huang 2011). The challenges identified in the coordination of the response to the 2008 Wenchuan earthquake emphasise the importance of establishing pragmatic emergency response plans which allow for the impacts of an earthquake.

4.5 Comparison between international case studies

Comparison between the 1994 Northridge, 1999 Chi-Chi, and 2008 Wenchuan earthquakes has enabled significant requirements of post-earthquake response to earthquake-induced landslides to be identified. Although the management of slope failures after each earthquake varied, underlying similarities within the response structures have emphasised the value of the following:

- Pre-earthquake planning

  For both the Northridge and Chi-Chi earthquakes, pre-planning and preparation of post-earthquake response to geotechnical hazards enabled rapid deployment of geotechnical professionals and scientists to implement assessment of coseismic landslides and management of risk to life safety. For the 1994 Northridge, California earthquake this was achieved through the development of the ATC-20 post-earthquake building safety evaluation guidelines. The response to the 1999 Chi-Chi, Taiwan earthquake was improved through pre-earthquake research programs which developed pre-disaster preparedness, and enabled response methodologies to be established. Subsequently, processes were developed for the deployment of geotechnical professionals and the management of reconnaissance data using GIS.
- National-level involvement in the geotechnical response

  For all three international earthquakes the geotechnical response to coseismic landslides was managed from a government level and executed through the utilisation of geotechnical professionals and scientists. Emphasis of the importance of national level involvement in the response was highlighted after the 1999 Chi-Chi earthquake through the development of a deployment structure managed by a government science agency (National Centre for Research on Earthquake Engineering and National Science Council of Taiwan). Similarly, the use of the ATC-20 post-earthquake response guidelines commissioned by government agencies in the United States of America and the state of California emphasised the role of higher level organisations in the management of geotechnical response to coseismic landslides. Furthermore, in response after the 2008 Wenchuan, China earthquake, the Chinese government deployed the immediate response, relief, and management of landslide dams post-earthquake. In addition to this, decisions by the Chinese government to relocate towns also prompted the requirement for detailed post-earthquake engineering geological assessments of slope failure hazards.

Further to these geotechnical response requirements, focus on the management of landslide dams during the response to the 1999 Chi-Chi, Taiwan earthquake and the 2008 Wenchuan, China earthquake, emphasised the requirement for prioritisation of secondary hazards based on risk to life safety.

Comparison between the Chi-Chi, Northridge, and Wenchuan earthquake has enabled recurrent issues or challenges to be identified within responses to earthquake-induced landslides. In the aftermath of all three earthquakes, accessibility became a significant concern which emphasised the issue of slope instabilities impacting on transportation routes. For all three earthquakes, this impeded emergency relief efforts and in some cases temporary access routes were required to gain access to areas isolated by slope failure. The increased susceptibility of slopes post-earthquake leading to further failure was an issue identified in all three earthquakes, which hindered the execution of emergency response and reconstruction by causing further damage and presented continuing life safety risk. Further slope failure post-earthquake caused further loss of life after the Chi-Chi and Wenchuan earthquakes.

Each earthquake exhibited a varying extent of coordination within the response to earthquake-induced landslides which was dependant on the degree of pre-earthquake preparation and previous experience in disaster response. For both the Northridge and Wenchuan earthquakes the reviewed literature indicated that the scale of the earthquake exceeded the capacity of response resources and pre-earthquake response plans. Furthermore, lack of pragmatic response plans and lack of communication between agencies involved in the response were significant recurring issues within the three historical earthquakes. Typically these deficiencies were not specific to the geotechnical component of the response, rather were implied for the wider emergency response to the earthquakes. The earthquake response deficiencies, priorities and tasks discussed in this chapter shed light on the common response requirements that can be addressed in future response preparation and planning.

4.5.1 Progression of geotechnical response activities

The similarities between the 1994 Northridge, 1999 Chi-Chi, and 2008 Wenchuan earthquakes have informed the development of a temporal framework for coseismic landslide response (Figure 4.5). The framework presents the critical tasks which took place during the response after the three international earthquakes, and informs of the timeframes in which these response mechanisms have occurred. The progression of critical tasks provides insight into the progression of common priorities during geotechnical response to earthquake-induced landslides. Developing a framework for post-earthquake landslide response is constructive because it can inform future earthquake response planning and preparation.

Timeframes of response activities have been developed from reviewed literature from the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes. Time categories such as days, months and years have been used to present a generalised progression of response activities through time. The six key response mechanisms presented in Figure 4.5 have been identified through their occurrence in all three of the post-earthquake response, and the contribution to addressing the risk posed by earthquake-induced landslides. Descriptions of these response mechanisms, and the contribution that these activities make to the response as observed in the historical earthquake case studies have been detailed in Table 4.4.

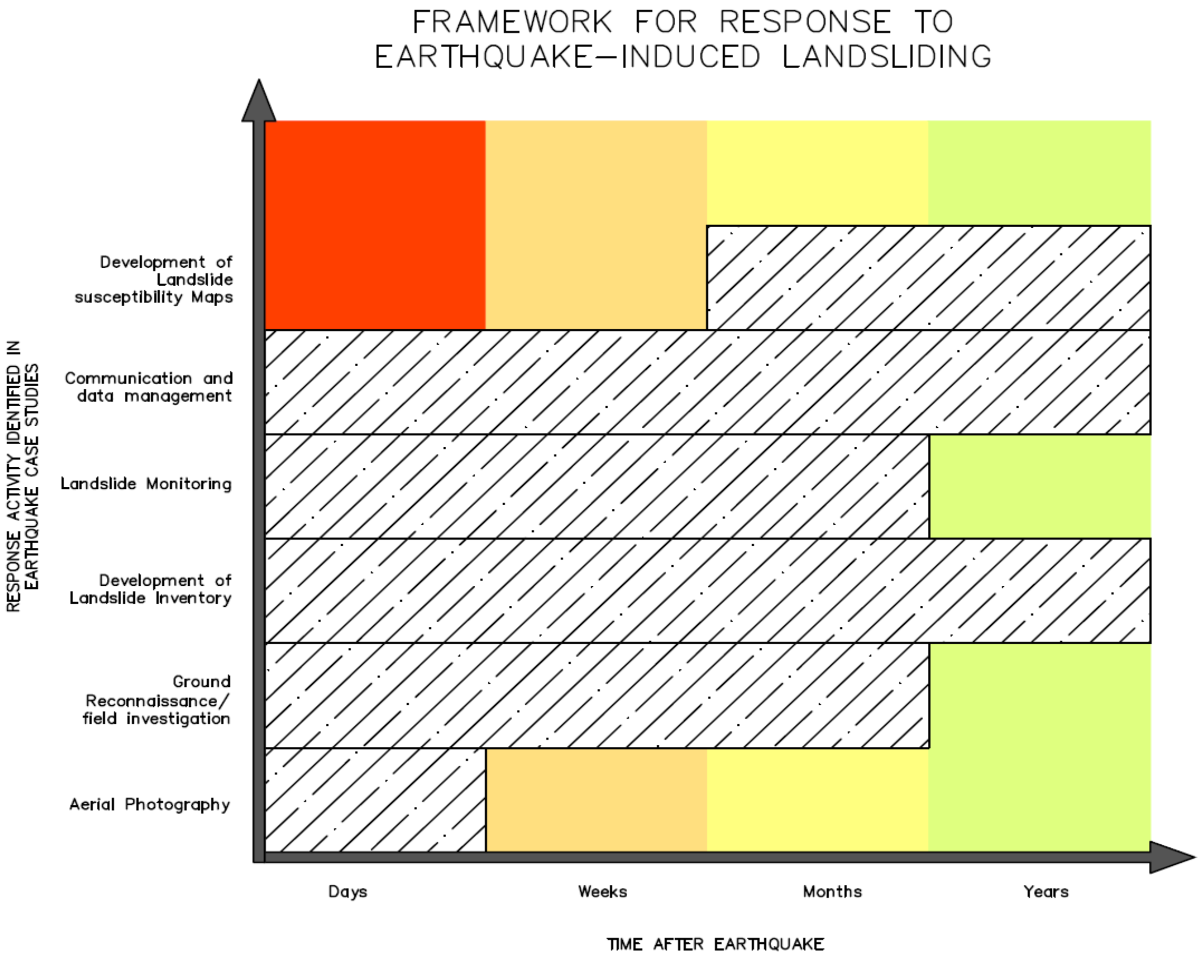


Figure 4.5: Interpretation of the temporal framework for geotechnical response to earthquake-induced landslides

Additional response techniques identified in the response to the Northridge, Chi-Chi, and Wenchuan earthquakes included the use of geological and geomorphological mapping and analysis of landslide material properties and slope stability. These techniques have not been included in the response framework because in reviewed literature, geological and geomorphological mapping and slope stability analysis was incorporated into the development of landslide susceptibility maps. For the basic response framework, these components have been included in Landslide susceptibility mapping.

Table 4.4: Description and temporal structure of post-earthquake response activities to earthquake-induced landslides from international earthquakes

Activity	Timeframe	Description of use in post-earthquake landslide response
Aerial Imaging and remote sensing	**2008 Wenchuan Earthquake** • Took place three days post-earthquake (Huang 2011) • Information used by China Geological Survey to locate landslides (Cui et al. 2011) **1994 Northridge Earthquake** • Hours after earthquake (Harp and Jibson 1995) • Undertaken by U.S Air force, images used by USGS and emergency planners (USGS 1996) **1999 Chi-Chi Earthquake** • Four days post-earthquake (Lin and Tung 2004) • Information used by Bureau of Soil and Water Conservation, Council of Agriculture (2000) (Lin and Tung 2004)	• Inform an initial impact assessment by assessing the extent of landsliding and provide information to develop landslide inventory and susceptibility mapping (Harp and Jibson 1995). • Comparing pre-disaster images to post-disaster images, provide insight into the extent of damage (Free et al. 2008). • Worst hit areas can be identified from aerial imaging so that response resources can be focussed on areas that are more extensively damaged or isolated after the earthquake (Keaton and DeGraff 1996). • Photographs can also be used as base maps for geologic and geomorphic mapping (Keaton and DeGraff 1996). • Assess the size of landslides and landslide dams (Cui et al. 2009). • Historic aerial imaging can be useful to help identify areas where historic landsliding has occurred. This can be valuable for understanding the pre-earthquake slope conditions in the area (Keaton and DeGraff 1996). • Limitations: Smaller landslides are less likely to be visible in the images (Harp and Jibson 1995).
Ground Reconnaissance and field investigations	**2008 Wenchuan Earthquake** • Commenced "immediately" (Tang et al. 2009) **1994 Northridge Earthquake** • Commenced "immediately" by USGS (USGS 1996) **1999 Chi-Chi Earthquake** • Commenced within one week under the direction of the National Centre for Research on Earthquake Engineering (Loh and Tsay 2001)	• Initial field inspections are useful for identifying the failure mechanism and extent of movement (Turner and McGuffy 1996). • Field investigations enable the collection of data such as GPS co-ordinates of geological features so information can be recorded to a database (Loh and Tsay 2001). • Ground reconnaissance work also gives the opportunity for basic measurements and material descriptions to be taken which can't be obtained from aerial reconnaissance. This can lead to assessment of the slope mechanics and risk of further failure (Hung 2000). • For landslide dams field observations of the height, width and composition of embankment materials could be obtained and used to quantify the associated risk threshold and recommend emergency treatment (Cui et al. 2009).
Landslide inventory	**2008 Wenchuan Earthquake** • Commenced "immediately" as part of emergency susceptibility mapping by (Tang et al. 2009) **1994 Northridge Earthquake** • Commenced several days post-earthquake for USGS (Harp and Jibson 1995) **1999 Chi-Chi Earthquake** • Data started to be collected days post-earthquake, continued years post-earthquake (Lin and Tung 2004)	• Landslide inventories are built up from site location information gathered from aerial imaging and ground reconnaissance work, and they provide a database of information for further slope stability analysis or hazard analysis (Harp and Jibson 1996; Harp et al. 2011). • Landslide inventories can be a useful resource to refine our understanding of the factors influencing the distribution of earthquake-induced landslides (Gorum et al. 2011).

Activity	Timeframe	Description of use in post-earthquake landslide response
Landslide Monitoring	**<u>2008 Wenchuan Earthquake</u>** • Monitoring of landslide dams commenced days after earthquake and continued for months (Chen et al. 2010; Cui et al. 2011). • Monitoring of the larger landslide dams was under the auspices of the Chinese government (Chen et al. 2010). **<u>1994 Northridge Earthquake</u>** • Weeks after earthquake regional ground deformation information (GPS measurements) collected (Parise and Jibson 2000) - Unclear if specific landslide monitoring took place. **<u>1999 Chi-Chi Earthquake</u>** • Ground motion information used in landslide analysis years after event (Lin and Tung 2004) - Unclear if specific landslide monitoring took place.	• Reconnaissance monitoring should be simple and easy to install so that immediate preliminary data on the mechanics and direction and rate of movement can be obtained (Keaton and DeGraff 1996). In the long term, instruments such as inclinometers, extensometers, and piezometers will be installed at a landslide site to measure movement and groundwater levels (Mikkelsen 1996). • Other examples of landslide monitoring can also include digital terrain modelling created from Light Detection and Ranging data (LIDAR). This can be useful for analysing the topography of the land (Townsend and Rosser 2012). Comparison of LIDAR data can also be used to give quantitative estimates of the amount of material that has moved during an event (Keaton and DeGraff 1996; Massey et al. 2012b). • Limitations: May be limited by availability of equipment post-earthquake. In the initial aftermath of an earthquake monitoring can include the use of simple "string line" tools set up across a landslide scarps which can be measured regularly until more accurate equipment such as GPS stations can be installed (Dellow et al. 2011).
Communication and data management	**<u>2008 Wenchuan Earthquake</u>** • Communication of monitoring information for landslide dams commenced days after earthquake (Cui et al. 2011), Media coverage played a big role in the communication of needs which directed response coordination (Earthquake Engineering Research Institute 2008) **<u>1994 Northridge Earthquake</u>** • Communication of impact assessment commenced hours to days after earthquake (USGS 1996). Existing communication systems facilitated this communication (USGS 1996) **<u>1999 Chi-Chi Earthquake</u>** • Communication and management of data collected in during field assessment commenced days after the earthquake using communication systems developed by NCREE (Loh and Tsay 2001).	• Communication and distribution of information is an important component of disaster and hazard assessment particularly in the immediate aftermath of an earthquake event. Effective communication of information should enable timely assessment of hazard and risk, and ensure that people inhabiting the hazard areas have access to hazard information (Loh and Tsay 2001). • Communication was important after the earthquake because raw data collected from scientific findings can be distributed to researchers, the public, and authorities. Communications through fact sheets, magazines, and the internet is useful for this (USGS 1996).
Landslide Susceptibility Maps	**<u>2008 Wenchuan Earthquake</u>** • Development of landslide susceptibility maps commenced days post-earthquake to assist in emergency management of refugees (Tang et al. 2009). **<u>1994 Northridge Earthquake</u>** • Work to update existing susceptibility maps commenced months post-earthquake - estimation of timeframe based on Parise and Jibson (2000). Development of maps continued years post-earthquake (Wills et al. 2011). **<u>1999 Chi-Chi Earthquake</u>** • Commenced months after earthquake and continued years after earthquake - estimation based on Lin and Tung (2004).	• Susceptibility maps are useful for aiding planning development, emergency preparedness and predicting how disruptive an earthquake can be in a variety of earthquake scenarios of different magnitudes and locations (Harp and Jibson 1995; Tang et al. 2009). • Development of susceptibility maps involves combining information gathered from ground reconnaissance, aerial mapping, material properties, slope stability analysis, geological and geomorphological mapping and slope monitoring. A long term advantage of creating susceptibility maps is that for future events this resource may show where landslides are most likely to occur, which would be useful for land use planning and planning for future earthquake response (Wills et al. 2011). • Limitations: Some susceptibility maps do not include the landslide potential of higher frequency trigger events such as rainfall and earthquakes in the region (Wills et al. 2011).

4.5.2 Progression of priorities during geotechnical response

Comparison between the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes provides a general framework for geotechnical response priorities. The progression of activities presented in Figure 4.5 can be used to contextualise response priorities with response tasks. Figure 4.6 presents correlation between Northridge, Wenchuan and Chi-Chi earthquakes to inform a generic progression of geotechnical response priorities.

For the response to Northridge, Wenchuan and Chi-Chi, the initial priority encompassed protection of life safety and execution of an impact assessment to inform emergency response. Over time, the priorities transitioned to the assessment of continuing risk (long term risk) associated with earthquake-induced landslides and landslide dams. Generally, this transition took place months after the earthquake and potentially reflected the transition from earthquake response to earthquake recovery.

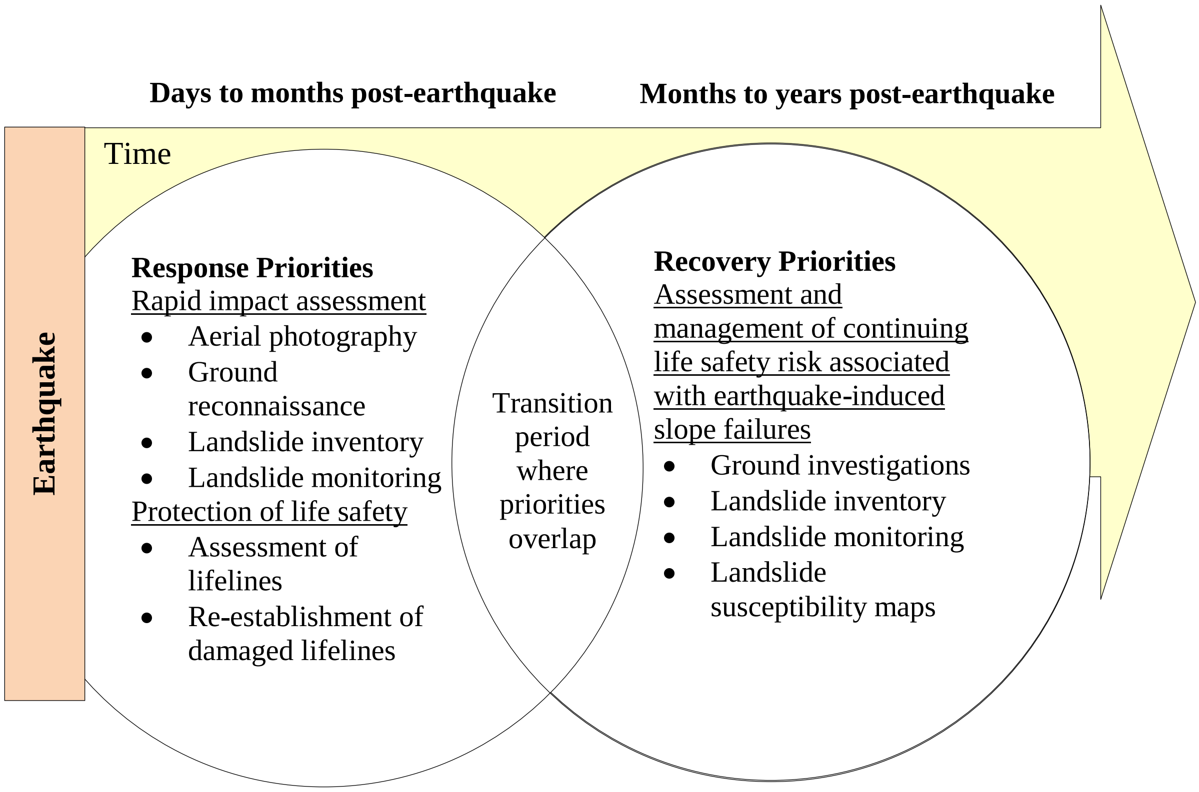


Figure 4.6: Transition of priorities during geotechnical response to earthquake-induced landsliding

4.6 Summary

Information from historical international earthquakes has been used to inform a basic temporal framework for geotechnical response to coseismic landslides. Six response requirements have been identified in the post-earthquake response to landslides induced by the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes. Temporal changes in response tasks provide insight into changes in priorities during response to earthquake-induced landslides. Initially the geotechnical response commenced after each earthquake focussing on the protection of life safety from imminent risk, overtime this changed to analysis and management of continuing risk associated with landslides.

Comparisons between international earthquakes has also enabled common issues in geotechnical response to be identified. Accessibility of transportation routes impacted by earthquake-induced landslides was a significant issue that was emphasised in the three international earthquakes. Furthermore, increased slope instability post-earthquake resulted in further loss of life and damage to infrastructure during response and recovery to the Chi-Chi and Wenchuan earthquakes. Continuing slope failure impeded post-earthquake response and hindered recovery and reconstruction.

The response to the Chi-Chi, Taiwan and Northridge, California earthquakes highlight the value of implementing pre-event planning to guide post-earthquake response. After both earthquakes, the response to earthquake-induced landslides was encompassed in government response framework. This enabled the response to be executed rapidly post-earthquake, with the roles of governing organisations clearly defined. Comparison between the Chi-Chi, Wenchuan, and Northridge earthquakes can be used to contextualise response techniques implemented during the Canterbury Earthquake Sequence with international response techniques.

Chapter Five: Analysis of geotechnical response following large earthquakes – comparison between the Canterbury Earthquake Sequence and international examples

5.1 Introduction

The aim of this chapter is to examine the post-earthquake geotechnical response to the 22nd February 2011 earthquake during the Canterbury Earthquake Sequence (CES), as detailed in Chapter Three, to provide comparison with historical international earthquake discussed in Chapter Four.

Comparison has been based on the response progression after the 22nd February 2011 earthquake because it was the first event in the CES which caused widespread co-seismic slope failure in the Port Hills. Furthermore, the widespread slope failure that occurred resulted in the requirement for a geotechnical response group to form. In comparison, response to the 4th September 2010 and 13th June 2011 earthquakes took place under contractual agreements between Christchurch City Council (CCC) and local geotechnical professionals. Furthermore, the 4th September 2010 earthquake resulted in significantly less land damage in the Port Hills. Rapid deployment and reassessment within sectors still took place after the 13th June 2011 earthquakes, however the risk to life safety was less of an issue as the response to 22nd February 2011 earthquake as many houses had already been evacuated in the affected area.

Comparison between the 22nd February 2011 earthquake and international earthquakes was conducted in three stages: firstly, a conceptual model of the geotechnical response to the CES was developed to highlight the temporal progression of requirements for response to coseismic landslides. Secondly, significant themes from the CES were identified to outline the methodology for post-earthquake geotechnical response. Thirdly, the challenges and successes identified in the CES were critically evaluated through comparison to the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes.

Results of the comparison between earthquakes provide insight into aspects of the geotechnical response that can be refined for future earthquakes in New Zealand.

5.2 Conceptual temporal model of geotechnical response

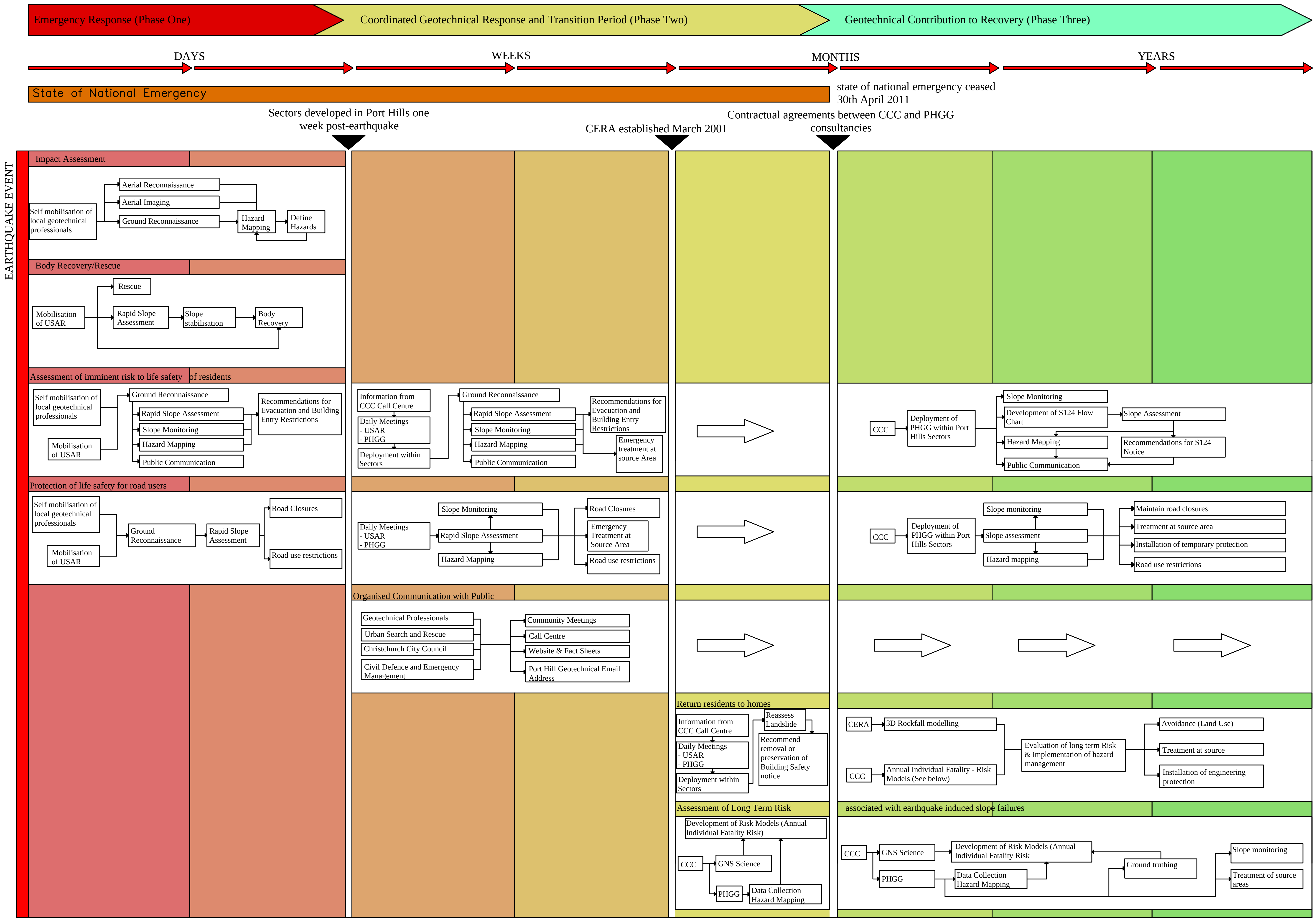
5.2.1 Overview of geotechnical response phases

The 22nd February 2011 earthquake during the Canterbury Earthquake Sequence (CES) has provided insight into the progression of requirements, priorities, and hazard management techniques that are implemented during geotechnical response to earthquake-induced slope failure. Based on the evolution of these components of the response to the 22nd February 2011 earthquake, a temporal model has been developed. The purpose of the temporal model is to identify an expected progression of geotechnical response to assist pre-planning of emergency management (Figure 5.1).

The model has been divided into three sequential phases based on temporal changes in priorities and requirements of the geotechnical response to the 22nd February 2011 earthquake. These phases are discussed in further detail in sections 5.2.2, 5.2.3, and 5.2.4, with a brief overview provided below. Response to earthquake-induced slope failures after the Northridge, Chi-Chi and Wenchuan earthquakes (Chapter Four) have been used to inform the development of phases for geotechnical response. The three phases are:

- **<u>Phase One - Immediate emergency response</u>**
  Timeframe: hours to approximately seven days post-earthquake
  Response requirements included the mobilisation of geotechnical resources to undertake rapid slope assessments which led to recommendations for evacuations and building use restrictions for the protection of life safety. At this stage in the response considerable effort was devoted to developing the coordination of the geotechnical response, and as such leadership roles emerged and systems for deployment and data collection were developed.

Figure 5.1: PHASED POST-EARTHQUAKE GEOTECHNICAL RESPONSE TO COSEISMIC LANDSLIDING AFTER THE 22nd FEBRUARY 2011 EARTHQUAKE



- **<u>Phase Two - Coordinated Geotechnical Response</u>**

  Timeframe: One week to several months post-earthquake

  From one week after the 22nd February 2011 earthquake the deployment coordination and communication between geotechnical professionals had improved. Moreover, site assessment and data collection methods became increasingly standardised. The focus on protection of life safety continued with the execution of further slope assessment to inform evacuations and building use restrictions. Towards the end of Phase Two, focus started to shift onto the assessment of the long-term risk associated with earthquake-induced slope failures. Assessment of long-term risk refers to the evaluation of ongoing hazard presented by slopes that failed during the CES. For example, the increased susceptibility of rockfall source areas resulted in ongoing failure post-earthquake which necessitates continuing hazard assessment and management.

- **<u>Phase Three - Geotechnical professional's contribution to earthquake recovery</u>**

  Timeframe: Commenced several months post-earthquake and continued for years post-earthquake.

  Several months following the 22nd February 2011 earthquake, the coordination changed to include formal agreements between geotechnical professionals and local authorities. During Phase Three, the focus of the geotechnical response shifted to the assessment of long-term risk and the development of permanent risk management strategies for areas affected by earthquake-induced slope failure, including slope remediation and avoidance.

5.2.2 Emergency geotechnical response (Phase One)

In the initial phase of the geotechnical response, up to one week after the 22nd February 2011 earthquake, the first priority and main goal was to protect life safety by identifying geotechnical hazards and then evacuating areas affected by rockfall, cliff collapse and loess failures as quickly and as efficiently as possible. During the first week of the response, categorisation of the types of earthquake-induced landslides was developed based on ground reconnaissance and impact assessments. At this point there was little delineation between deep-seated slump failures in loess and tensile cracking in loess which was later interpreted as fissuring. Both required further investigation to derive the failure mechanisms.

Table 5.1 outlines the objectives and requirements of the geotechnical response during Phase One based on information presented in Chapter Three. Despite the lack of management structure to inform the geotechnical response coordination in the immediate aftermath of the 22nd February 2011 earthquake, the geotechnical response was well executed. Furthermore, the requirements to develop efficiency within the geotechnical response were identified within the first week post-earthquake which enabled the Port Hills Geotechnical Group (PHGG) to form. Development of the PHGG led to improvement in the execution of deployment, slope assessment and enforcement of evacuations.

Table 5.1: Phase one objectives and requirements during the immediate response to the 22nd February 2011 earthquake

Objectives	Key tasks	Requirements	Organisation involvement
Impact Assessment	• Communication with Civil Defence • Ground Reconnaissance • Aerial Reconnaissance	• Communication pathways with Civil Defence • Resources for ground reconnaissance and aerial reconnaissance (i.e. vehicles, aircraft)	• Geotechnical professionals • GNS Science • Regional and local Civil Defence
Assessment and management of imminent life safety risk	• Mobilise geotechnical response • Assess imminent risk from rockfall, cliff collapse, landslide and loess failure • Communicate risk to Emergency Management entities • Remove residents from imminent risk exposure (evacuations and building safety notices by USAR and CDEM) • Group meetings	• Basic landslide monitoring equipment • Meeting location for geotechnical group • Aerial images • GIS Database • Standardised data collection • Communication pathways with Civil Defence	• USAR • Geotechnical professionals • GNS Science • Regional and local Civil Defence Building Safety Evaluation Team • Christchurch City Council
Rescue and body recovery	• Temporary slope stabilisation for body recovery • Debris removal	• USAR training	• USAR • Regional and local Civil Defence
Development of response coordination and management	• Organise deployment • Standardise data collection and slope assessment • Categorise slope failures	• Daily meetings • Communication between entities and individuals involved in response • Define assessment and data collection methodologies	• USAR • Geotechnical professionals • GNS Science • Regional and local Civil Defence • Christchurch City Council

During the same time frame similar tasks were undertaken during the response to the 1994 Northridge, 2008 Wenchuan, and 1999 Chi-Chi earthquakes. These included:

- Aerial Reconnaissance,
- Ground Reconnaissance,
- Building safety evaluation,
- Slope stability assessments, and
- Slope monitoring.

In comparison to the objectives outlined in Table 5.1, the immediate response to the 1999 Chi-Chi and the 1994 Northridge earthquakes were guided by pre-existing geotechnical response frameworks and consequently there was less need to develop coordination in the first days of the response. Conversely, reviewed literature did not imply that the geotechnical response to the 2008 Wenchuan, China earthquake was guided by pre-developed response framework in the immediate aftermath of the earthquake. However, the implementation of the Wenchuan Earthquake Disaster Recovery and Reconstruction Act one month after the earthquake did guide the execution of impact assessments and hazard assessments to inform the relocation of towns. The implementation of the recovery act in China occurred within a similar timeframe post-earthquake to the repeal of the Canterbury Earthquake Response and Recovery Act (2010) which was superseded by the Canterbury Earthquake Recovery Act (2011) one month after the 22nd February 2011 earthquake.

A significant difference between the immediate response to the CES and the 1999 Chi-Chi and 2008 Wenchuan earthquakes was the requirement for assessment and management of landslide dams. For both the Chi-Chi and Wenchuan earthquakes the focus on landslide dams was dominant in the aftermath of the earthquake due to the consequence of dam failure, and inundation of water and debris downstream of the hazard. Despite this difference, similarity can be identified in the prioritisation of hazards in the immediate aftermath of each earthquake based on the consequence to life safety. In the aftermath of the 22nd February 2011 earthquake during the CES, management of cliff collapse, rockfall, and loess failures that impacted roads or residential areas were prioritised according to their impact and threat to life safety. This emphasises the focus on imminent risk immediately post-earthquake.

5.2.3 Coordinated geotechnical response (Phase Two)

In Phase Two of the geotechnical response to the 22nd February 2011 earthquake, protection of life safety continued to be maintained as the response priority. The objectives and requirements of Phase two are outlined in Table 5.2. During Phase Two a transition took place which resulted in the focus shifting from protection of life safety from imminent risk, to the development of risk models to evaluate the ongoing (or long-term) risk associated with coseismic landslides. Phase Two commenced one week after the 22nd February 2011 earthquake, and continued until the state of national emergency ceased two months later (30th April 2011).

Table 5.2: Phase two objectives and requirements during the response to the 22nd February 2011 earthquake

Objectives	Key activities/tasks	Requirements	Organisation involvement
Protection of life safety	• Mobilise geotechnical response • Ground Reconnaissance • Assess slope failures • Communicate risk to Emergency Management entities • Remove residents from imminent risk exposure (evacuations and building safety notices) • Group meetings • Slope stabilisation – scaling, bolting, mesh	• Basic landslide monitoring equipment • Meeting location for geotechnical group • Aerial images • Communication pathways with Civil Defence • Involvement of local construction contractors	• USAR (Start to lessen in involvement, by end of phase no longer involved) • Geotechnical professionals (PHGG) • GNS Science (technical support) • Regional and local Civil Defence Building Safety Evaluation Team • CCC • Local Contractors
Data collection and management	• Data collection • Transfer of data to database • Development of maps to inform further response	• GIS Database • Standardised data collection • Geotechnical Professionals with GIS experience	• GNS Science • Geotechnical professionals
Assessment of on-going risk associated with earthquake-induced slope failure	• Data collection • Methodology for risk assessment • Reassessment of slope failures following aftershocks	• Data • Client supporting analysis	• GNS Science • CCC • PHGG
Public communication	• Community Meetings • Port Hills Geotechnical email address • Fact Sheets	• Meeting location • Deliver fact sheets • Acquire email addresses of residents	• USAR • PHGG • GNS Science • Regional and local Civil Defence • CCC

Phase Two is also differentiated from Phase One through the following changes:

- Fewer requirements to develop coordination within the geotechnical response. By this stage deployment was facilitated through the development of the Port Hills sectors, daily meetings, and through the CDEM and CCC Call Centre. These developments were established within the first week of the response to the 22nd February 2011 earthquake.

- The requirement for slope assessments to provide recommendations for evacuation and the application of Building Safety Evaluation notices decreased throughout the three weeks post-earthquake. As such the involvement of organisations such as USAR also decreased.
- Mapping of tension cracks, boulders, and debris deposits increased during the three weeks post-earthquake as the requirement for evacuations decreased. Mapping enabled a hazard database to be developed to prepare for longer term detailed risk assessment or further research after the emergency period had ended.
- The Christchurch City Council (CCC) started to increase its involvement to prepare for continuation of the involvement of geotechnical professionals once the state of national emergency ended (30th April 2011).
- Communication with the public became a central part of Phase Two of the geotechnical response as it became apparent during Phase One that there was a high demand for technical information from the public.
- More sophisticated slope monitoring equipment such as continuous GPS and survey systems were deployed to monitor slope movements.

During the same time frame for the response to the 1994 Northridge, 2008 Wenchuan, and 1999 Chi-Chi earthquakes the following tasks were undertaken:

- Ground Reconnaissance,
- Development of a landslide inventory,
- Development of landslide susceptibility maps,
- Building safety evaluation,
- Slope stability assessments, and
- Slope monitoring.

These tasks indicate a similar focus on assessment of life safety risk, however also emphases transition to assessment of long term risk. As discussed in Chapter Four, the development of landslide susceptibility maps generally commenced months after the earthquake and consequently did not initiate immediately in Phase Two. Typically the development of landslide susceptibility maps and landslide inventories start to address the analysis of long-term risk associated with earthquake-induced slope failures (Harp and Jibson 1996). As such, the response to the three historical earthquake case studies supports the conclusion that during phase two (weeks to months post-earthquake) the response starts to focus on the assessment and management of on-going risk from earthquake-induced landslides.

Further supporting evidence of the transition to assessment of on-going risk can been seen after the 2008 Wenchuan, China, earthquake where approximately one month post-earthquake engineering geology hazard assessments were conducted to identify locations for the relocation of towns impacted by coseismic slope failures. The implementation of these assessments emphasises the transition from post-earthquake response to recovery, and highlights the importance of evaluating long term risk associated with slopes that had undergone failure during the earthquake.

5.2.4 Geotechnical contribution to earthquake recovery (Phase Three)

Phase Three describes the geotechnical involvement during the recovery period which commenced at the end of the state of national emergency (30th April 2011) after the 22nd February 2011 earthquake. The objectives for Phase Three of the geotechnical response are detailed in Table 5.3.

Table 5.3: Phase Three objectives in the geotechnical response to the 22nd February 2011 earthquake

Objectives	Key activities/tasks	Requirements	Organisation involvement
Management of on-going risk associated with earthquake-induced landslides	• Gather information to inform assessment of long term risk • Reassessment of slopes to inform application of S124 Notices under the Building Act • Provide advice for mitigation measures • Inform strategic decisions regarding land use and engineering protection	• Formal contract between geotechnical professionals and governing authority • Development of Risk Model • Quantification of cost in relation to solutions	• PHGG • Christchurch City Council • GNS Science (Risk model)

Although protection of life safety continued to be a priority, the requirement for residents to be returned to their homes, or permanently evacuated, also becomes important. With this in mind the assessment of long term risk from coseismic slope failures induced by the 22nd February 2011 earthquake became a significant priority. Geotechnical professionals also continued to provide their services for rapid slope assessments after major aftershocks such as the 13th June 2011 earthquake.

During the recovery phase the level of detail and investigation of rockfall and cliff collapse increased during the development of the GNS risk model. Furthermore, characterisation of slope failures in loess was further addressed. To inform the analysis of rockfall, cliff collapse and loess failures, activities such as subsurface investigations, monitoring, and geomorphological and geological mapping were undertaken to provide detailed information of slope failures. Comparably, the response to the 1994 Northridge, 2008 Wenchuan, and 1999 Chi-Chi earthquakes also presented a similar focus where analysis of landslide susceptibility became increasingly thorough in each region. Landslide inventories were developed after each of the three international earthquakes with the aim to inform susceptibility analysis.

During the recovery from both the Chi-Chi and Northridge earthquake, the seismic hazard model for each region was updated to integrate the latest understanding of seismic hazard. The extensive damage and destruction of buildings after the 2008 Wenchuan earthquake emphasised the requirement to reconsider the seismic design and construction of buildings, particularly schools and hospitals (Zifa 2008). Furthermore, ground motions experienced during the earthquake exceeded design values outlined in the 2001 Chinese Seismic Code, which necessitated revision of the guidelines to inform the rebuild process (Free et al. 2008; Zifa 2008). Similarly, significant updates were made to the national seismic hazard model (NSHM) for the Christchurch region after the 22nd February 2011 earthquake, based on the understanding that the seismic hazard had increased due to the ongoing earthquake sequence (Mcverry 2012). Because seismic codes such as the New Zealand NSHM influence building design and construction, development of seismic codes post-earthquake reflects the requirement to continually improve understanding of seismic hazard and thus aiming to improve resilience in the area impacted.

5.3 Identification of geotechnical response themes

Development of the conceptual model of the geotechnical response to the Canterbury Earthquake Sequence (CES) has enabled the identification of significant themes which contributed to the execution of management and assessment of coseismic landslides. Based on the information presented in section 3.4 of Chapter Three, and the interpretation of the response progression into phases in section 5.2, the following themes have been identified:

1. Geotechnical response coordination and management, including internal communication within the geotechnical response group
2. Protection of life safety, includes the assessment of hazards and the enforcement of evacuations
3. Public communication

Figure 5.2 presents an interpretation of how the themes of coordination, life safety, and public communication relate based within the structure of the geotechnical response after the 22nd February 2011 earthquake.

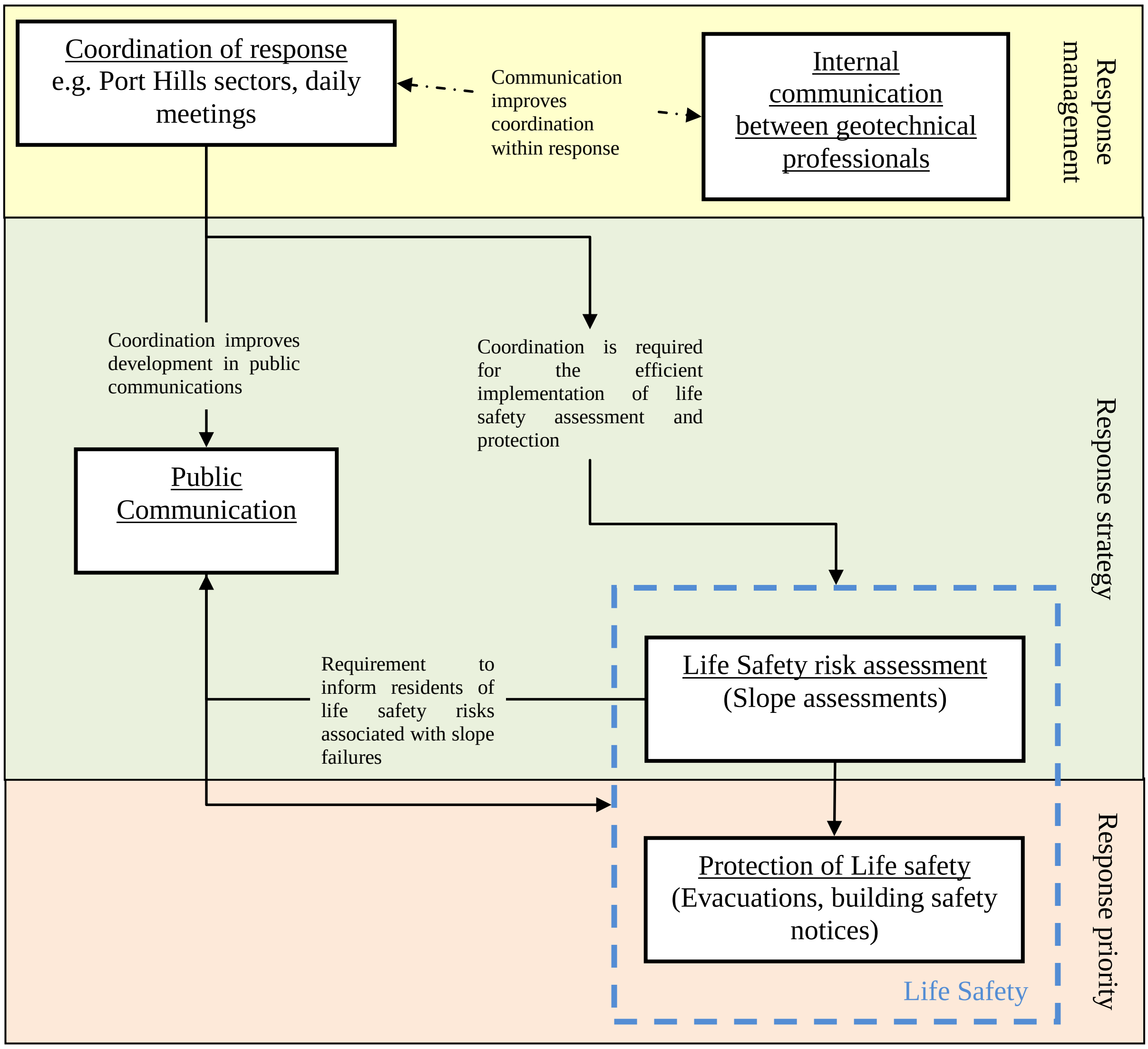


Figure 5.2: Interaction between main themes in geotechnical response to the 22nd February 2011 earthquake during the Canterbury Earthquake Sequence

The themes listed above have been divided into three aspects based on the overarching structure of the geotechnical response to the earthquake. Aspects of the geotechnical response include following:

- **Geotechnical response priority:**

  The priority describes the primary focus of the response which was the underlying motive behind the response tasks and the development of an organisational strategy. From the CES case study and the international earthquake case studies, the protection of life safety was maintained as the priority. This can be identified from the focus on management of rockfall, cliff collapse, and loess failure hazards during the response to the 22nd February 2011 earthquake. For the 1999 Chi-Chi and 2008 Wenchuan earthquakes, the emphasis on protection of life safety could be observed in the prioritisation of landslide dams. Similarly for the 1994 Northridge earthquake this could be seen in the use of the ATC-20 guidelines for post-earthquake building safety evaluation to restrict use of structures affected by land damage.

  Although the protection of life safety has been maintained as the priority during the responses to the case study earthquakes, the context in which it is addressed changed throughout time. Immediately after each earthquake (hours to days post-earthquake) protection of life safety is required from imminent risk. Conversely, months after an earthquake, protection of life safety from long term risk or on-going slope hazards becomes the focus.

- **Geotechnical response strategy:**

  The strategy for geotechnical response refers to the tasks implemented to protect life safety. During the response to the 22nd February 2011 earthquake tasks such as slope assessments informed building use restrictions and evacuations. Public communication such as community meetings and the distribution of fact sheets contributed to informing residents of the hazards, and thus communicating the requirements for risk management techniques such evacuations and building use restrictions that were implemented to protect life safety from imminent risk. Similarly, strategies to protect life safety from imminent were implemented after the Chi-Chi and Wenchuan earthquakes with particular emphasis on the management of landslide dams through the excavation of spillways and implementation or monitoring. Furthermore, the strategy for protection of life safety during the response to Northridge was conducted through the implementation of the ATC-20 guidelines (Appendix I).

When the response priority shifts to address protection of life safety from long term risk associated with earthquake-induced landslides, permanent protection measures such as engineered protection structures or changes in land use are required to address the continuing risk. This was observed after the 2008 Wenchuan earthquake with the relocation of towns based on assessment of geological hazards present at the previous town location.

- **Geotechnical response management and coordination:**

  The management of the geotechnical response refers to organisational techniques which were implemented to coordinate geotechnical professionals and scientists during the response. The division of the Port Hills into sectors, and the development of the Port Hills Geotechnical Group, provide examples of management techniques that were implemented during the geotechnical response to the 22nd February 2011 earthquake in the CES. To encourage the development of coordination, daily group meetings were established 48 hours after the earthquake which facilitated communication internally between geotechnical professionals within the PHGG and externally between PHGG and CDEM or CCC.

  The format for geotechnical response to the 1999 Chi-Chi earthquake provides an example of a management technique whereby reconnaissance teams were deployed to conduct specific tasks, and subsequently report the information collected to a centralised GIS database coordinator. The purpose of the management strategy was to ensure that post-earthquake reconnaissance was conducted in efficiently, and scientists and professionals involved in the response were coordinated. Less is known about the management techniques implemented during the response to the Northridge earthquake, however the timely deployment of the geotechnical scientists from United States Geological Survey (USGS) implies that procedures for coordination of earthquake response was present at a national level in advance of the event.

Based on the case study analysis of the geotechnical response to the 22nd February 2011 earthquake (CES), interactions between the “response priority”, “response strategy” and “response coordination” can be derived. Figure 5.2 presents the interaction between the three aspects to the geotechnical response, and indicates the influence of communication on developments in coordination. Information gathered from interviews (Chapter Three) implies that where improvements in communication occurred internally within the geotechnical response group (PHGG), there were improvements in the coordination of the response. For example, once daily meetings were established 48 hours after the earthquake, the coordination within the group improved and subsequently the development of sectors and a standard slope assessment and data collection methodology was established.

5.4 Synthesis of geotechnical response themes

To provide further detail of the response themes identified in section 5.3, the challenges and successes within the geotechnical response to the 22nd February 2011 earthquake during the Canterbury Earthquake Sequence (CES) have been examined. Examination of the challenges and successes has enabled the specific requirements of each of the themes to be identified while providing insight into underlying issues within the response management. Comparison between the CES case study and the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes has provided evidence to discuss the similarities and differences within the geotechnical responses. Subsequently, conclusions have been drawn regarding the specific requirements of geotechnical response to earthquake-induced landslides. Table 5.4 provides a synthesis of challenges identified in the CES which accentuate fundamental underlying management and operational issues during the post-earthquake geotechnical response to the CES. Boxes shaded blue in Table 5.4 represent correlations between fundamental issues and challenges identified in the geotechnical response.

Examination of the geotechnical response to the 22nd February 2011 earthquake during CES with comparison with international earthquakes has provided confirmation around the importance of pre-planned frameworks for emergency response, and the significance of transparent linkage between Civil Defence and Emergency Management (CDEM) and geotechnical professionals (Table 5.4). The deficiency of these two response requirements in the response to the 22nd February 2011 earthquake has been highlighted through the challenges in the geotechnical response management and public communication. Furthermore, lack of internal communication between geotechnical professionals and Urban Search and Rescue also hindered developments in coordination, and caused uncertainly in the definition of roles within the response. Challenges within slope assessments and protection of life safety (tactical level tasks) were heightened by the lack of response framework and reliance on rapid qualitative risk assessment. Further detail of these fundamental issues in light of the challenges identified in the case study earthquakes is presented in sections 5.4, 5.6 and 5.7.

Table 5.4: Correlation between challenges and fundamental issues in geotechnical response to 22nd February 2011 earthquake during the Canterbury Earthquake Sequence

			Fundamental issues					
		Chapter Section	*No framework to guide response*	*Lack of linkage with CDEM*	*Lack of internal communication*	*Reliance on expert judgement*	*Lack of detailed information*	*Lack of Training*
Challenges identified in the Geotechnical response to the 22nd February 2011 earthquake (CES)	**Developing Coordination**	5.4.1						
	Role definition	5.4.2						
	Formal reporting system	5.4.3						
	Database development	5.4.4						
	Consistency in assessment of risk	5.6.1						
	Risk assessment uncertainty	5.6.2						
	Integration with building safety evaluation	5.6.3						
	Public Communication	5.7						

Concurrently, pragmatic techniques for geotechnical response have been identified through activities or developments which improved coordination and efficiency. Table 5.5 presents a summary of the influences from techniques listed in section 5.1.2. Boxes shaded blue in Table 5.5 represent correlations between successful response techniques and subsequent improvements recognised in the geotechnical response. Developments such as the Port Hills sectors and the PHGG became essential to the protection of life safety because of their influence on improvements within response coordination. Internal communication within the geotechnical response group has been identified as a catalyst for the development of improvements within the response. Further detail of the successful techniques identified in the case study earthquakes are presented in section 5.5.

Table 5.5: Correlation between successful techniques and improvements in the geotechnical response to Canterbury Earthquake Sequence

			Improvements in geotechnical response			
		Chapter section	*Improvements in response coordination*	*Improvements in efficiency of response*	*Improvements in internal communication*	*Improvement in data management*
Successful components of geotechnical response	**Development of geotechnical response group**	5.5.1				
	Geographic sectors of impacted area	5.5.2				
	Daily meetings within geotechnical response	5.5.3				
	Development of GIS Database	5.5.4				

5.5 Challenges within post-earthquake coordination of geotechnical response

5.5.1 Developing coordination post-earthquake

Based on the case study analysis of the geotechnical response to the Canterbury Earthquake Sequence (CES) and historical earthquakes, post-earthquake coordination was identified as a main theme in section 5.3. Examples of the importance of coordination during the CES can be identified in the aftermath of the 22nd February 2011 earthquake, which also emphasised the challenge of developing coordination post-earthquake without the guidance of pre-planning. Duplication of slope assessments by geotechnical professionals, and the lack of communication between responding agencies within the first week of the response to the 22nd

February 2011 earthquake emphasised that the existing coordination, or lack thereof, was insufficient to execute the response efficiently, and inevitably management systems were required to develop during the emergency response. The lack of guidelines detailing how to assess risk associated with earthquake-induced slope failures in an urbanised area augmented this issue, and resulted in variation within slope assessment methodologies in the early stages of the response. Consequently, the development of centralised coordination became critical however was a gradual process because of the lack of pre-planning by the tactical and strategic level organisations involved.. Furthermore, ground motions experienced during the 22nd February 2011 exceeded the probabilistic seismic hazard for Canterbury region and caused land damage in the Port Hills that could not be foreseen.

Development of coordination within the response group after the 22nd February 2011 earthquake was further complicated in that many local geotechnical professionals involved in the geotechnical response were also involved with managing damage to their own homes and supporting families who had experienced trauma from the earthquake. As such, family commitments, personnel stress and exhaustion influenced the involvement of some local geotechnical professionals in the response. Moreover, the lack of pre-planning for an earthquake of this scale resulted in the capabilities of local geotechnical scientists and professionals being overwhelmed by the extent of land damage in the Port Hills.

Development in coordination was emphasised by the modification of relationships between organisations throughout the response until the end of the state of national emergency (30th April 2011). The progression of these interactions shows the use of iterative learning to develop a framework which addresses the response requirements. Changes within organisation interactions also highlight the initial lack of role definition, and further emphasises the absence of pre-planning leading to the requirement of coordination development post-earthquake.

In comparison to the Canterbury Earthquake Sequence, the response to the 1994 Northridge and 1999 Chichi earthquakes were guided by pre-developed coordination frameworks at a government level. The framework for post-earthquake geotechnical reconnaissance for the Chi-Chi earthquake defined the interactions between government organisations such as the National Science Council (NSC) and reconnaissance teams by providing a reporting structure within the response. The structure implemented during the response to the Chi-Chi, Taiwan earthquake is described further in section 4.3.3, of Chapter Four. The implementation of the response structure meant that organisational roles were clearly delineated pre-earthquake, and information gathered during the response could be easily communicated and integrated within emergency planning.

Similarly, the ATC-20 guidelines and the response capabilities of United States Geological Survey (USGS) ensured that post-earthquake coordination was maintained at a national level in the immediate aftermath of the earthquake. USGS scientists were deployed rapidly to undertake an impact assessment to identify the extent of earthquake-induced landslides. Information collected post-earthquake could then be communicated to emergency managers. Comparison between the CES, Chi-Chi and Northridge earthquakes provide evidence of the importance of pre-planning for post-earthquake response. Furthermore, the implementation of a management structure for geotechnical response from a government level has been conducted in historical earthquakes such as the Chi-Chi and Northridge earthquakes. Considering that both Taiwan and California both are historically seismically active regions and consequently have developed post-earthquake geotechnical response structures, their example implies that for future earthquakes in New Zealand geotechnical response should be integrated with national level emergency management.

5.5.2 Role definition within geotechnical response

Case study analysis of the CES has emphasised the importance or role definition immediately post-earthquake. Role definition was an issue which evolved primarily from the lack pre-planning and thus lack of identified roles during the first week of the response to the 22nd February 2011 earthquake during the CES. Geotechnical professionals who were involved immediately post-earthquake identified that Civil Defence Emergency Management (CDEM) was the managing organisation for the response, however found it difficult to identify individuals within the Emergency Operation Centre (EoC) who were overseeing the geotechnical component of the response. The following issues may have contributed to this:

- The integration of local and regional Civil Defence and Emergency Management (CDEM) response centres within the first three days of the response to the 22nd February 2011 earthquake. Refer to Appendix F for further detail.

- The predominant focus of CDEM in the first week of the response was assessment and management of building damage in Christchurch City and surrounding suburbs, including damage associated with liquefaction and lateral spreading.

The execution and management of the geotechnical response to earthquake-induced landslides was not included within the existing CDEM framework and planning, and consequently was detached from CDEM response days after the earthquake. Linkage was formed through the involvement of CDEM science liaison personnel who intuitively identified the requirement to include the geotechnical response to landslides in the Port Hills into the wider CDEM response and emergency management. Increasing communication between geotechnical professionals, Urban Search and Rescue (USAR), and CDEM was essential for progressively developing coordination between organisations involved with the Port Hills. For example, when communication between geotechnical professionals and USAR increased days after the 22nd February 2011 earthquake, a system was developed for informing the execution of evacuations based on slope assessments. Consequently the roles of each group became increasingly defined. Section 3.4.1, Chapter Three, provides a description of the development of the system.

Role definition was also a challenge for USAR, who were unrecognised by some geotechnical professionals to have the authority to enforce evacuations. This issue highlights a lack of knowledge around New Zealand emergency response capabilities, and emphasises the lack of integration between engineering professionals and CDEM.

The benefits of integrating the geotechnical response with the CDEM planning pre-earthquake would include:

- Information for impact assessment post-earthquake - geotechnical professionals who were responding in the Port Hills were a useful source of information for emergency managers regarding the impact of the earthquake in the hilly suburbs,
- Subsequent integration between assessments of slope failure hazards and building safety evaluation. Prior to the 22nd February 2011 earthquake geotechnical hazards such as rockfall had not been included in the structure for building safety evaluation, and consequently this was required to develop post-earthquake.

Comparatively, as discussed in section 5.5.1 the framework for post-earthquake response after the 1999 Chichi, Taiwan earthquake provided clear delineation of emergency response roles and organisational responsibility which informed role definition. Government science agencies such as National Science Council (NSC) were clearly defined as the managing organisations for geotechnical science response. As such, information collected during ground reconnaissance was communicated to the governing organisation to inform further emergency management. The examples of the response to the CES and Chi-Chi earthquakes indicate that for a well executed response to initiate immediately post-earthquake, organisations involved should be aware of the capabilities and authorities of other organisations involved prior to the event. Furthermore, pre-planning of post-earthquake response would address the issue of role definition.

5.5.3 Deficiencies within post-earthquake formal reporting

The importance of reporting information post-earthquake has been identified in the case study analysis of the CES, and has been further supported by the response to the Chi-Chi and Wenchuan earthquakes. Establishing balance between formalised reporting and meeting the tactical requirements of the response was a challenge after the 22nd February 2011 earthquake during the CES. Local government and the geotechnical community were unprepared for the scale of earthquake and subsequent widespread landsliding which occurred during the 22nd February 2011 earthquake. No formal data collection system was utilised during the immediate geotechnical response and as such observations were recorded as brief notations or verbally communicated to other personnel involved in the response. Although this can be an unreliable form of correspondence, in the immediate response there was little time for formalised reporting systems because of the extensive requirement for rapid life safety protection.

The response to the 2008 Wenchuan earthquake demonstrates that reporting of information gathered during slope assessments is important so that the impact of the earthquake can be appreciated and emergency responders can plan further response (Tang et al. 2009; Huang 2011). After the 2008 Wenchuan earthquake, rapid slope susceptibility analysis was imperative for informing the placement of refugees and temporary housing. As such, timely reporting of susceptibility information was crucial to emergency management. This example highlights the requirement for balance between reporting requirements and the execution of assessments so that the demands for reporting are achievable.

5.5.4 Database development

Analysis of the geotechnical response to the CES and the 1999 Chi-Chi earthquake has indicated that GIS database development is a crucial component of the post-earthquake response and emergency management. Although the development of a GIS database became a successful component of the response to the 22nd February 2011 earthquake, the process of forming the database was challenging as there was no pre-existing platform which was suitable for post-earthquake response. For this reason, the development of a centralised database became imperative during the immediate response. Initially development of the GIS database was slowed due to restricted access to computers and buildings, and further by the requirement to obtain GIS datasets from local authorities in Christchurch. This hindered the timely integration of collected data early on in the response and further affected the ability of the geotechnical response group to use aerial images as base maps for recording field observations.

In contrast, the response to the 1999 Chichi, Taiwan earthquake was supported by a GIS platform that had been established prior to the earthquake occurring. GIS maps of each county had been developed as part of research programs to improve hazard mitigation, pre-disaster preparedness, and emergency response in Taiwan. Utilisation of a pre-developed database allowed for timely integration of information for analysis which informed emergency management decisions by enabling areas worst hit by the earthquake to be identified. Indicatively this aspect of the Chichi response was well integrated with the responding organisations and based on the requirement for GIS databases after the 22nd February 2011 earthquake, provides an example of what may be useful for New Zealand.

5.6 Successes within post-earthquake coordination of geotechnical response

5.6.1 Development of a formalised geotechnical response group

The geotechnical response to the 22nd February 2011 earthquake during the CES has emphasised the value of a coordinated response group composed of geotechnical professionals and scientists to execute slope assessments. The development of the Port Hills

Geotechnical Group (PHGG) was an influential and successful component of the post-earthquake response, despite group formation occurring in a high pressure emergency situation where geotechnical response had not been incorporated into the emergency management planning. PHGG was involved in the protection of life safety through the assessment of slope failures, and the provision of recommendations for evacuation and building use restrictions.

The PHGG consistently progressed towards improvement of coordination with the development of geographic sectors in the Port Hills, the establishment of regular meetings, and development of a reporting structure within one week post-earthquake. Group cooperation facilitated discussion regarding site assessment decisions, and provided a support system between group members that became invaluable. In a post disaster situation it is recognised that altruistic values and unity within the communities often prevail over conflict and competitiveness (Goltz et al. 2001). Interviews with participants from PHGG indicated that the group exhibited this same unity within the response capability, whereby geotechnical professionals from a variety of consultancies were able to work towards a common priority of protecting of life safety in the Port Hills.

Less is known about how the geotechnical professionals and scientists interacted in the response to the Northridge, Chi-Chi and Wenchuan earthquakes. Reconnaissance groups that were developed after the 1999 Chi-Chi, Taiwan, earthquake were required to develop an internal structure for data collection. This implies that internal group coordination existed, however reviewed literature has not provided further detail on this.

5.6.2 Post-earthquake division of geographic sectors

The response to the 22nd February 2011 earthquake has highlighted the benefit of dividing the area impacted by coseismic slope failure into geographic sectors to improve coordination of the geotechnical response. The Port Hills sectors were identified by interview participants as a successful component of the response because they facilitated uniform and systematic deployment and organisation of geotechnical assessment teams. Macfarlane and Yetton (2013) also identified sectoring as a key lesson learnt from the emergency response to earthquake-induced landslides after the 22nd February 2011 earthquake. The development of geographic sectors within the Port Hills occurred in the first week post-earthquake and became a fundamental component of the geotechnical group coordination which continued to guide the deployment of geotechnical professionals years after the event.

Coordination through sectors meant that geotechnical engineers or engineering geologists were not responding on an individual basis, rather within consultancies, and ensured that all areas of the Port Hills were included in the assessment. The development of sectors also facilitated the communication with the Civil Defence and Emergency Management (CDEM) response centre because it enabled information gathered from the call centre to be communicated directly to the geotechnical professional responsible for a particular area and vice versa. Based on reviewed literature, it is unclear whether similar methods were conducted after the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes.

5.6.3 Regular meetings within geotechnical response group

Geotechnical professionals who were involved in the 22nd February 2011 earthquake during the CES, and who participated in interviews, indicated that daily meetings were important for forming contacts and receiving information about the situation outside of their own sector. As discussed in section 5.4.1, daily meetings were initiated approximately 48 hours post-earthquake and were imperative to the development of coordination within the geotechnical response. The meetings also enabled geotechnical professionals to meet with representatives from USAR, CCC, CDEM and EQC. Macfarlane and Yetton (2013) identified daily meetings as a crucial component of the organisation of the response to the 22nd February 2011 earthquake, which enabled lessons and observations to be shared within the group. Less is known about the implementation of regular meetings during geotechnical response to the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes. Furthermore, reviewed literature did not indicate whether meetings were an imperative component of response coordination.

5.6.4 Development of a centralised GIS database

As highlighted in section 5.4.4, the development of a GIS database was a successful component of the geotechnical response to the 22nd February 2011 earthquake during the CES. The development of a centralised database became an important component of PHGG response as it enabled data collection and analysis to take place in a central location. Data analysis was enabled spatial appreciation of the extent of impact in the Port Hills which facilitated discussions around the coordination of the emergency response and evacuation planning. The database was a useful resource for hazard communication through the production of base maps for recording information during field investigations and emergency response. A similar technique was used in the response to the 1999 Chi-Chi, Taiwan earthquake which has been further discussed in section 5.4.4.

5.7 Challenges within protection of life safety during post-earthquake response

5.7.1 Consistency within qualitative hazard and risk assessment

Case study analysis of the 22nd February 2011 earthquake during the CES indicated that reliance on expert opinion, and the lack of prepared methods for assessing earthquake-induced slope failures presented an issue with consistency of slope assessments. Maintaining consistency of qualitative risk assessment can be difficult due to the subjective nature of this type of assessment. Qualitative assessment can also lend itself to diverse interpretation depending on the scope of the problem and cultural elements associated with the assessment (Crozier and Glade 2004).

The lack of pre-existing assessment procedures meant that a standard slope assessment format was not utilised in the immediate aftermath of the 22nd February 2011 earthquake, which resulted in variation in the assessments. To address this issue the following tactics were implemented to improve consistency within the first week of the response:

- Regular communication through daily morning meetings of Port Hills Geotechnical Group.
- Communication between geotechnical professionals during slope assessment, i.e. geotechnical professionals used discussion as a form of peer review before a hazard management strategy implemented. This method of peer review was useful, particularly when there was uncertainty regarding the mechanism of failure, likelihood of failure, and consequences of failure which contributed to the assessment of risk.

- A standard assessment format for data collection was developed (Appendix G). The purpose of the format was to record consistent information and standardised the qualitative risk assessment procedure.

Case study information from the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes did not indicate whether consistency in assessment of secondary geological hazards was an issue during post-earthquake response. The use of the ATC-20 guidelines during the response to the Northridge earthquake indicates that this issue may have been addressed through pre-planning.

5.7.2 Uncertainty during post-earthquake hazard and risk assessment

During the response to the 22nd February 2011 earthquake, uncertainty within hazard assessment was present because of the reliance on expert judgement and visual observations in the absence of detailed information and time for thorough assessment. Uncertainty in the assessment of environmental hazards is unavoidable, however it does not necessarily result in the prevention of a pragmatic assessment provided allowance is made for the consequences relating to the degree of uncertainty in the assessment (Ramsey 2009). Furthermore, the influences of individual beliefs, circumstances, and complexity within society is inescapable in the assessment and management of risk (Smith and Petley 2009). As such, uncertainty is an issue that is commonly required to be addressed in both quantitative and qualitative risk assessment (Ramsey 2009). Post-earthquake risk assessment is no exception to this.

During the response to the 22nd February 2011 earthquake, there were several factors which contributed to uncertainty in post-earthquake risk assessment of earthquake-induced landslides. Firstly, uncertainty in hazard assessment varied depending on the failure mechanism. For example, rockfall and cliff collapse could be characterised by the rapid release of material from a slope of which the debris could be observed during assessment. However, complication arose in the assessment of rockfall and cliff collapse when source areas were assessed to estimate a likelihood of further failure, and provide an approximation of the area potentially exposed to further failure. Furthermore, cliff collapse areas were isolated by the evacuation of residents in proximity to the failure; however, evacuating residents from rockfall affected areas was complicated by the requirement to estimate a probable rockfall run out and delineate a likely impact area.

Rockfall run out became difficult to estimate immediately post-earthquake because of the requirement to consider factors such as topography, vegetation, boulder size, and likelihood of further failure. This often led to a conservative hazard management approach in the immediate aftermath of the earthquake. The requirement to delineate areas exposed to rockfall was maintained a priority throughout the response and recovery to the 22nd February 2011 earthquake. Subsequent to the emergency response, further detailed analysis such as rockfall modelling was conducted to remove uncertainty from the qualitative rockfall assessment in the days to weeks after the earthquake.

Rapid hazard characterisation of failure in loess was complex in the days after the 22nd February 2011 earthquake. Geotechnical professionals were required to characterise the failure mechanism based on visual observation of the prevalence and distribution of tensile cracking and compression features. Tensile cracking in loess, which was later interpreted as "fissures in loess" (refer to section 1.4.2.3, Chapter One for description), was not conducive to typical slump failure behaviour based on post-earthquake observations by geotechnical professionals. As such, it was difficult to estimate the risk posed by the hazard as the failure mechanism was not immediately obvious. As discussed in section 1.4.2.3 of Chapter One, the characterisation of some slope failures in loess in ongoing at the time of writing this thesis.

Conversely, loess failures that were noticeably characterised as deep seated slump failure in the days after the 22nd February 2011 earthquake were maintained a priority for weeks post-earthquake because of the consequences of further failure i.e. large residential area could have been impacted. Survey networks and Global Positioning Systems (GPS) monitoring equipment were installed days after the 22nd February 2011 earthquake to collect information regarding the direction of movement and amount of displacement to further inform the characterisation of hazards. Over time, monitoring equipment indicated that limited down slope movement had occurred despite aftershocks, and the deep seated slump failures were no longer considered high risk. This example emphasises the uncertainty within hazard assessment of earthquake-induced slope failures in the immediate aftermath of an earthquake and provides insight into changes in perception of risk throughout time. The example also highlights the importance of evaluating the rate of failure and consequences of failure for deep-seated slump hazards in the aftermath of an earthquake.

Uncertainty in hazard assessment can result in a non-conservative estimation of the likelihood of further failure. This was highlighted after the 13th June 2011 earthquake when rockfall source areas that were considered to be low risk after the 22nd February 2011 earthquake released further material. Despite this, generally geotechnical professionals were confident that their decisions regarding rockfall risk after the 22nd February 2011 earthquake were defendable as no further deaths occurred. However, when the 13th June 2011 earthquake occurred many of the areas affected by earthquake-induced slope failure had already been evacuated.

Uncertainty is also present in the quantification of imminent risk from earthquake-induced landslides where external factors can influence the suitability of hazard management techniques. For example, in the aftermath of the 22nd February 2011 in some extreme cases, some residents were not able to be removed from their homes in the conditions and in doing so would run the risk of loss of life. With this mind, the question arises whether is it appropriate to evacuate based on risk of slope failure if evacuation itself could cause loss of life. In this context balance between risk from further slope failures and risk from external factors needs to be considered. Furthermore, this emphasises the requirement for involvement of agencies such as Urban Search and Rescue (USAR) who are trained in dealing with risk in this context. It also emphasises that it would be appropriate to assess how imminent the risk is on a case by case basis bearing in mind external components.

Based on the case study analysis of the CES, uncertainty within risk assessment was a common issue post-earthquake, and was in most cases unavoidable particularly in the context of hazard characterisation which was based on visual observations and limited monitoring data. Development of pre-planned recommendations for post-earthquake slope failure risk assessment would have been helpful, however it could be limited by estimating the likely types of slope failures pre-earthquake. Conversely, the ATC-20 guidelines have addressed this by outlining probable post-earthquake slope failure hazards and detailing recommendations for hazard management. Aside from this, risk assessment uncertainty was not a concept that was discussed in the reviewed literature for the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes.

5.7.3 Integration of geotechnical hazard and building safety evaluation

Case study analysis of the CES indicated that post-earthquake building safety evaluation conducted by structural engineers was a component of the response to the 22nd February 2011 earthquake which was not integrated with geotechnical assessment of geotechnical hazards. Despite operational procedures being established within the first week of the response to improve this, it would have been useful to have established guidelines prior to the event. The Californian Applied Technology Council guidelines "ATC-20 *Procedures for Post-Earthquake Safety Evaluation of Buildings"* (Appendix I) provide an example of integration between geotechnical assessment and the application of building safety notices. Aside from the ATC-20 guidelines, it is unclear from reviewed literature whether this integration was present during the response to the 1999 Chi-Chi and 2008 Wenchuan earthquakes.

Advantages of providing a framework where the assessment of earthquake-induced slope failure hazard is incorporated into building safety evaluation include:

- Rapid building safety evaluation teams with a structural focus would be aware that a building use restriction notices may be applied where no structural damage is present, only geotechnical hazard such as rockfall (NZSEE 2011),
- Consistency in slope assessments and recommendations for building safety evaluation would improve if geotechnical professionals were trained under the basis of the CDEM building safety evaluation framework.

A developed framework should address the assessment of property exposure to geotechnical hazard. Furthermore, presumably if a building/structure is exposed to slope failure hazard, it may be that the property boundary in which the structure is situated may be exposed to the same hazard. This poses a question regarding the applicability of building use restrictions for geotechnical hazard, where restrictions to property access may be required. These are issues that should be addressed within the integration of geotechnical hazard assessment with building safety evaluation. It is obvious from the case study analysis of the CES and the 1994 Northridge earthquake that integration between geotechnical hazard assessment and building safety evaluation is required.

5.8 Challenges within post-earthquake public communication between geotechnical response groups and residents

5.8.1 Public communication

The response to the 22nd February 2011 earthquake indicates that communication with the public affected by geotechnical hazards was imperative for informing residents of the post-earthquake life safety risk. Due to the lack of integration with Civil Defence and Emergency Management (CDEM) during the first week of the response to the 22nd February 2011 earthquake, dissemination of information to the public regarding the emergency response was poorly addressed and heavily reliant on individual communication between geotechnical professionals and Port Hills residents. The high demand for information from Port Hills residents regarding enforcement of evacuations, building use restrictions and risk from slope failure hazards indicates that a strategy for public communication should be implemented immediately post-earthquake. The requirement for communication with residents was identified by the CDEM science liaison who became highly involved in the coordination of pubic communication, despite this being outside the scope of their role. Because of the involvement of the science liaison, geotechnical hazard fact sheets were distributed and public meetings were established approximately two weeks after the 22nd February 2011 earthquake. Although these methods were well received, the task of public communication should have been managed within the Public Information Management (PIM) sector of CDEM in accordance with the Christchurch City local civil defence emergency management arrangements (Sinclair 2008).

Interview information indicated that meeting the demand for information from the public during community meetings was often an exhaustive task for geotechnical professionals who were highly involved with communication with residents at community meetings and on an individual basis. Public communication was important because residents needed to understand the risks associated with each of the slope failure hazards. Communicating this risk through geotechnical professionals who were involved with slope failure risk management was a transparent and efficient method however many geotechnical professionals found the responsibility of communicating information to the public difficult because they had had no previous experience or training in presenting information to the public. It would be effective to develop a framework where specific geotechnical professionals were assigned the task of public communication during post-earthquake response. This may result in less involvement with slope assessment, however will ensure that public communication is informed by an experience geotechnical professional. This would be useful because the example of the 22nd February 2011 earthquake indicates that the task of communication should be addressed as a priority during the emergency response and executed consistently and efficiently.

Public data availability was a priority after the 1994 Northridge, California earthquake to ensure residents were informed of post-earthquake hazards. The techniques for public communication used in the Northridge earthquake highlight the need for timely dissemination of hazard information which is communicated in a format familiar to residents. Information availability commenced days after the earthquake through the implementation of fact sheets, internet and magazines (USGS 1996). This emphasises the importance of establishing a framework for reporting of ground reconnaissance information to inform the public. Reviewed literature for the 1999 Chi-Chi and 2008 Wenchuan earthquakes does not specifically indicate the methodologies used for public communication.

5.8.2 Involvement of territorial authorities

The geotechnical response to the 22nd February 2011 earthquake during the CES has provided an example of how territorial authorities can influence post-earthquake public communication where no pre-earthquake planning has delineated a strategy. Towards the end of the state of national emergency (30th April 2011), organisations such as Christchurch City Council (CCC) and the Canterbury Earthquake Recovery Authority (CERA) became increasingly involved in the management of earthquake-induced landslides from the 22nd February 2011 earthquake. As these organisations became more involved issues arose around the release of information based on the requirement for consistency from territorial authorities.

At this point, public demand for information was high, and the strain in public communication from higher level organisations made it difficult for geotechnical professionals to meet the demands of both the public and the local authorities. Because the welfare of residents was affected by the release of information around the response in the Port Hills, it was obstructive to allow political coordination or lack thereof to influence the disclosure of information. Residents were heavily reliant on the response capability of governing organisations, and as such required transparent communication during the development of a management strategy.

Although reviewed literature from the Northridge, Chi-Chi and Wenchuan earthquakes did not indicate the same issue, disruption of public communications post-earthquake during the CES provides a local example of the necessity for a pre-planned response framework which delineates organisational roles and provides objectives for public communication. Pre-earthquake preparation and emergency response should ensure that an appropriate public communication methodology is developed and executed post-earthquake.

5.9 Summary

The 22nd February 2011 earthquake during the Canterbury Earthquake Sequence (CES) has provided a local case study for the evaluation of post-earthquake geotechnical response to coseismic landslides. Based on the information presented in Chapter Three, a progression of requirements for geotechnical response to the 22nd February 2011 earthquake has been identified. Subsequently the geotechnical response has been divided up into three post-earthquake phases which represent temporal changes in response priorities, requirements and task. The three phases include:

Phase One - Emergency geotechnical response,
Phase Two - Coordinated geotechnical response,
Phase Three - Geotechnical involvement with earthquake recovery.

The geotechnical responses to the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes have provided discussion around the applicability of the proposed phased geotechnical response model. This analysis has been used to inform recommendations to refine future post-earthquake response to coseismic slope failure. Temporal changes in response requirements can be used to inform emergency managers for pre-earthquake response planning.

Analysis of the geotechnical response to the 22nd February 2011 earthquake during the CES has enabled several themes to be identified. These themes are: coordination, life safety and public communication. The interaction between these themes presents an overview of the geotechnical response methodology and the importance of conducting management strategies to pursue protection life safety. Further examination of the main themes and issues during the CES with comparison to the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes has emphasised the importance of the following requirements for executing geotechnical response:

- A pre-planned framework for post-earthquake geotechnical response,
- Integration of geotechnical response with national level emergency management such as Civil Defence and Emergency Management (CDEM), and
- Internal communication between geotechnical professionals and scientists involved in the response to earthquake-induced landslides.

The lack of these requirements in the CES hindered the implementation of slope assessments which required for informing the protection of life safety, and slowed the progression to Phase Two of the response. Furthermore, internal communication contributed to significant improvements in the response coordination. Four successful strategies that improved the coordination of the geotechnical response in the CES were:

- The development of the a formalised geotechnical response group,
- The division of the area impacted by coseismic landslides into geographic sectors,
- Regular meetings within the geotechnical response group, and
- The development of a centralised GIS database.

One of the major issues identified in the geotechnical response to the CES was the absence of pre-planned guidelines. As such, recommendations for future planning for post-earthquake geotechnical response to coseismic landslides should consider the successes and issues highlighted in this Chapter.

Chapter Six: Future geotechnical response to earthquake-induced landslides

6.1 Introduction

The purpose of this chapter is to present discussion concerning recommendations for pre-earthquake preparation and post-earthquake management of geotechnical response. Comparison between the Canterbury Earthquake Sequence (CES) and historical earthquakes such as the 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes in Chapter Five has highlighted the necessity for planning of post-earthquake response. Significant requirements, issues and successes identified within the response to the CES and international earthquakes have provided foundation for recommendations for geotechnical response. The outcomes of this Chapter can be used to inform planning for future post-earthquake response to coseismic landslides.

6.2 Requirements of geotechnical response to earthquake-induced slope failure

Based on the analysis of the CES and historical earthquakes, the priority of geotechnical response to earthquake-induced slope failure is the protection of life safety. The organisational requirements to address the protection of life safety include:

- Early implementation of a coordination strategy for response management of geotechnical hazards, so that minimal emphasis is required on the development of a management structure during the emergency response.
- Clear integration between geotechnical professionals and national emergency management operations such as Civil Defence and Emergency Management.
- Internal communication within the geotechnical response group, with the provision of regular meetings, and internal group structure.
- A framework which provides a methodology for post-earthquake risk assessment and risk management.

Based on the requirements for post-earthquake geotechnical response outlined in Chapter Five, recommendations have been made to provide guidance for future earthquakes. Guidance is required for the management of the response and for tactical tasks such as risk assessment and risk management. The development of national guidelines for geotechnical response would be an effective method for supplementing the need for guidance by providing a clear methodology for management and execution of the response.

Planning for future earthquakes needs to be adaptable to a variety of co-seismic geotechnical hazards and applications. Seismicity and slope instability in the Christchurch area prior to the CES did not provide insight into the extent of slope failure which occurred after the 22nd February 2011 earthquake. Furthermore, the cliff collapse failure mechanism had not previously been considered as a hazard in the Port Hills. Intuitively, with the example of the CES in mind, guidelines or recommendations developed for post-earthquake response must remain flexible so that unanticipated circumstances can be easily incorporated into the geotechnical response. Furthermore, processes developed for post-earthquake geotechnical response should be documented so that the recommended methodology for response can be easily communicated. Territorial authorities may develop a geotechnical response methodology specific to their area; however the response format should be recorded and distributed to parties contributing to the response.

6.3 Pre-earthquake planning for geotechnical response

6.3.1 Define a management structure for the geotechnical response

Establishing an adaptive management structure for response to large earthquakes prior to an earthquake occurring would be constructive so that post-earthquake protection of life safety is not hindered or delayed by the requirement to develop a management strategy. A management strategy would also improve the uniform application of life safety assessments and aim to coordinate immediate deployment of geotechnical professionals. Macfarlane and Yetton (2013) also identified that the immediate response post-earthquake can be haphazard if there is no guidance from pre-prepared management strategies.

The 1999 Chi-Chi, Taiwan earthquake and 1994 Northridge, California earthquakes provide examples of how a pre-developed management structure could assist the geotechnical response. For example, the geotechnical response to the Northridge earthquake was managed through the integration of geotechnical hazard assessment with ATC-20 *Procedures for Post-earthquake safety evaluation* and the rapid execution of regional slope failure impact assessment by the United State Geological Survey (USGS). The deployment of reconnaissance teams in the aftermath of the Chi-Chi earthquake (Chapter Two) was assisted by the development of an earthquake response framework which was overseen by government organisations.

Based on the information gathered in Chapter Four and Five a suggested management structure is shown in Figure 6.1. The following conclusions support the proposed structure:

- Group leadership is essential for centralising the coordination of the response and providing a conduit for communication between CDEM and the tactical geotechnical response contingent.
- Integration with CDEM has been identified as a crucial component of incorperating the geotechnical response with the wider earthquake response and is further discussed in section 6.3.2. The proposed structure (Figure 6.1) has detailed the CDEM controller, however; depending on the framework of CDEM reporting from the geotechnical response group it may be directed elsewhere within the leadership team.
- Sector leaders have been included in the proposed management structure because the role was developed through iterations of the coordination framework to the CES and remained until the PHGG ceased in 2013. Sector leaders are important because they oversee the hazard assessment and response requirements within their sector area.
- Assessment teams were required for risk assessments and to inform the evacuation of residents.

Within the final iteration of the PHGG coordination framework during the CES, an engineering team was developed to provide technical advice to the group. This has not been included in the suggested operating structure because technical capabilities may be supplemented through requirements within leadership roles. Furthermore, technical support is required less in the immediate aftermath of an earthquake due to the management of risk through evacuations rather than engineering structures or protection works. As such, if the requirement for technical support is present post-earthquake, a team with technical expertise may be required to form.

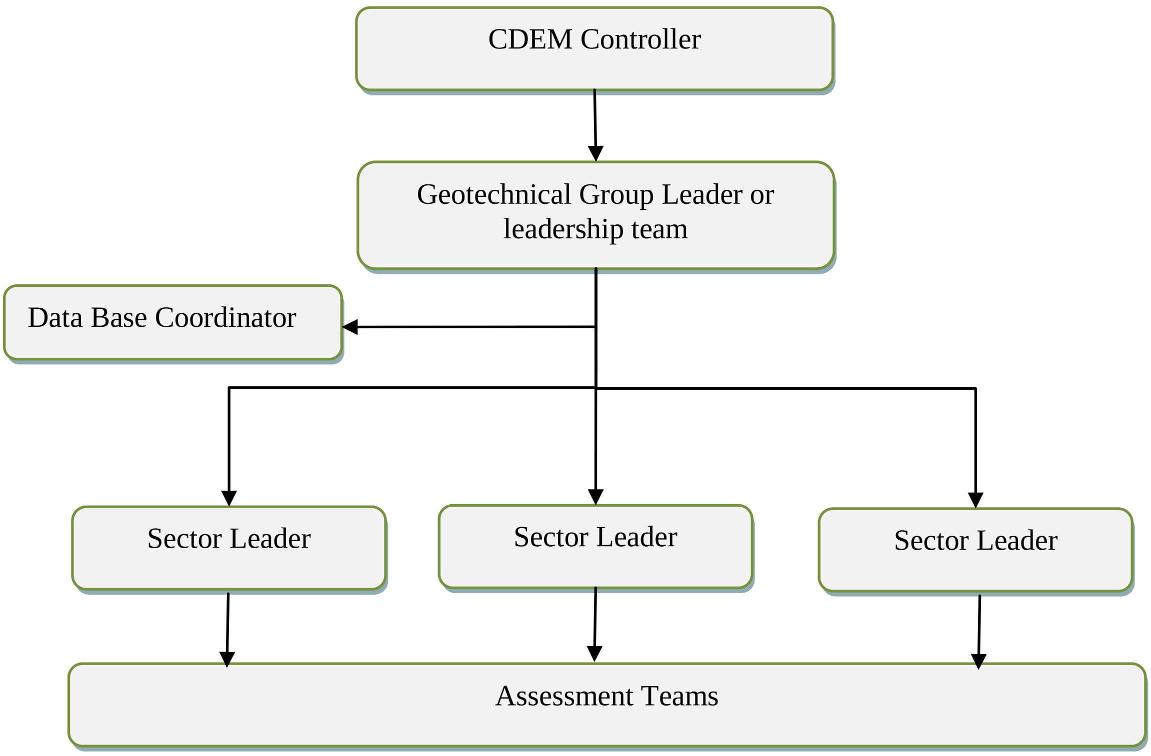


Figure 6.1: Suggested operating structure for geotechncial response

6.3.2 Designate key personnel within geotechnical response structure

In preparation for an earthquake, for urbanised areas of high seismicity and known landslide susceptibility it may be advantageous to designate key roles within the proposed geotechnical response operating structure. The requirement for this may be judged on the basis of regional risk assessment by local and regional authorities, and could include management of additional geotechnical hazards such as liquefaction and lateral spreading. With training conducive to the role requirements, the benefits of designating key personnel may include:

- Geotechnical professionals designated into roles prior to an earthquake will be aware of the emergency management strategies and CDEM communication requirements.
- Geotechnical professionals will be aware of roles within the response e.g. the role of USAR.
- In the event of an earthquake the geotechnical response can be activated immediately.

A similar framework is used for the Dam Safety Assurance Programme for medium and high risk Potential Impact Category (PIC) dams throughout New Zealand. To ensure the availability of a geotechnical group leader, two or three geotechnical professionals from each region should be trained in the New Zealand Coordinated Incident Management System (CIMS) to inform of existing emergency management systems used by emergency services and CDEM. Training should also include informing professionals and scientists of the geotechnical response operational structure. Sector leaders may be designated in the aftermath of the event depending on the number of sectors that are developed and the resources available.

Table 6.1 and 6.2 detail the proposed key roles involved in the geotechnical response based on the requirements of the Canterbury Earthquake Sequence and historical case study earthquakes i.e. 1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes. To avoid the issue of role definition as described in Chapter Four and Five it is imperative that Geotechnical professionals involved in key roles such as Geotechnical group leader are aware of the response methods and practices of CDEM and USAR.

Table 6.1: Proposed roles in the geotechncial response

Title	Role	Skills
Geotechnical Group Leader	• Volunteered geotechnical expert with training in geotechnical response systems • Report to Civil Defence and Emergency Management Controller and provide advice where appropriate • Responsible for dividing affected area into sectors and appointing sector leaders • Provide Technical Leadership, set inspection priorities and liaise with other agencies • Oversee group coordination and induction of volunteer inspectors	• Experienced in the geotechnical profession and management • Knowledgeable about Civil Defence and Emergency Management processes and systems. • Aware of the Civil Defence and Emergency Management legislation and understand the place of geotechnical assessment in the response process. • The Geotechnical Group Leader must be prepared to speak with the public at community meetings.
Database Coordinator	• Report to the Geotechnical Group Leader • Report directly to the Civil Defence and Emergency Management staff if spatial damage and risk information is required. • Responsible for developing the database, requesting information when required and passing on information from the database to CDEM.	• Experienced in the geotechnical profession and GIS. • Capable of leading a team if required (depending on the scale of the event)

Table 6.2: Proposed roles in the geotechncial response continued

Title	Role	Skills
Sector Leaders	• Manage the deployment of assessment teams within their sectors. • Ensure that the information flows from assessment teams to the database coordinator. • Report to the group leader regularly and meet regularly with other sector leaders • Maintain contact details of inspection team members and next of kin should be kept by sector leaders. • Track deployment locations and movements of assessment teams.	• Experienced in the geotechnical profession and have experience in management. • Sector leaders need to be prepared to be involved at community meetings within their sectors
Rapid Assessment teams	• Conduct rapid assessments as required • Report back to sector leader. • Make recommendations to USAR and CDEM for evacuation and Building Safety Notices based on the observations they have made regarding the slope failure. • Inspectors should work in pairs or assessment teams.	• Assessment teams must comprise of geotechnical professionals who have experience in the geotechnical profession • Assessments teams must be confident in their ability to make recommendations to USAR and CDEM based on the observations they have made regarding the slope failure. • The assessment teams must be prepared to communicate with the public on an individual basis or at community meetings.

6.3.3 Integration of geotechnical response with Civil Defence and Emergency Management

As recorded in Chapters Four and Five, the detachment of the geotechnical response from the Civil Defence and Emergency Management (CDEM) response hindered the integration of the geotechnical response within the wider emergency management. Due to the lack of linkage with CDEM the following challenges arose:

- Development in coordination was hindered by lack of integration with CDEM,
- Inconsistency in the integration of geotechnical hazard assessment with building safety evaluation,
- Delay in establishing effective public communication systems,
- Issues with role definition arose immediately post-earthquake, and
- No formal reporting system was present between CDEM and geotechnical professionals which led to prolonged acknowledgement of the issue within the Port Hills by CDEM Managers.

Pre-earthquake integration of geotechnical response capabilities in the CDEM response system would improve communication systems, role awareness and ensure that response methodologies conform to the requirements of CDEM. Coordination and agreement between geotechnical professionals, geotechnical scientists, USAR and Building Safety Evaluation teams must be developed so that there is integration of geotechnical hazard evaluation within Building Safety Assessments.

Since the CES occurred, the lack of linkage between CDEM and professional engineers within rapid building assessment in the response has also been highlighted as a major issue in the response to the event sequence despite guidance from '*Guidelines for Building Safety Evaluation during a State of Emergency'* developed by the New Zealand Society for Earthquake Engineering (NZSEE) (Brunsdon 2012; Brunsdon et al. 2012). It is clear that for the interface between CDEM and professional engineers to progress in New Zealand, systems need to be developed at a national level with the encouragement of legislative drivers. Due to these conditions previous attempts at developing response arrangements have not led to a conclusive result (Brunsdon 2012).

Despite the requirement for further integration at a national level, the NZSEE guidelines provided fundamental recommendations for building safety evaluation which aided the coordination of the response from structural engineers and building inspectors and ensured the Building Safety Evaluation process was under the direction of the Civil Defence and Emergency Management Controller. As such liability was addressed under Section 110 of the Civil Defence and Emergency Management Act 2002 (NZSEE 2011). Because the geotechnical response was not initially managed under the CDEM arrangements, initially liability became a concern for some volunteering geotechnical professionals. In comparison to the geotechnical response, the response from structural engineers and building inspectors was managed more effectively and as such provides a pragmatic example of the advantage of establishing response guidelines. Addressing liability issues prior to an earthquake occurring may also increase the number of willing volunteers in the aftermath of an emergency (NZSEE 2009).

6.3.4 Develop a register of geotechnical professionals

After a major earthquake or geotechnical hazard event such as the 22nd February 2011 earthquake where large scale slope failure occurred, local resources may be inadequate to execute the required assessment of life safety risk. Preparation of a register of geotechnical professionals who are able to assist in the event of an earthquake may reduce deficiency in local resourcing and enable efficient mobilisation for emergency response. By 2013 the Christchurch City Council (CCC) established a list of geotechnical consultancies that could provide geotechnical engineering advice which highlights the ongoing requirement for geotechnical professionals in the response to earthquake-induced slope failures.

The development of a pre-earthquake network would encourage awareness within the geotechnical community of emergency response procedures for geotechnical professionals and Civil Defence and Emergency Management. The network could be used to maintain communication and keep geotechnical professionals informed of geological hazards in the region. Prior awareness of landslide hazards and response procedures would aim to increase the efficiency of the emergency response. For the network to be successful, governing agencies such as CDEM, and territorial and regional authorities would need to agree to provide information updates on geotechnical hazards and emergency management strategies. An organisation such as the Institute of Professional Engineers New Zealand (IPENZ) may be required to oversee the network. Input from local universities and research institutes may also provide information around geotechnical hazard and local seismicity.

In a review of the integration of professional engineers in emergency response in New Zealand by Brunsdon (2012) it was noted that a similar register of professional engineers who can assist in civil defence emergency had been developed by IPENZ prior to the 4th September 2010 earthquake. Unfortunately the establishment of the register had only progressed to a preliminary stage at the time of the earthquake sequence (Brunsdon 2012). Noting the specialisation of engineers within the register of professional engineers would be beneficial, so that structural or geotechnical engineers can be extracted from the database. Contact information on the register should be updated regularly to ensure that in the event of an emergency the contacts are up to date.

The similar register established for the California Emergency Management Agency has been developed where over 6,000 professional who have been trained in either rapid safety evaluations or coordination are listed on the database (Brunsdon 2012). Specific credentials are required to be eligible for the database. This is useful information to include in a database due to the qualitative nature of rapid post-earthquake risk assessment and the reliance on expert judgement. Inconsistencies in knowledge, skill level and confidence between professionals have the potential to result in inconsistent evaluations of risk (NZSEE 2011). Without further research it is difficult to delineate to what extent professional registration or experience would be required for geotechnical professionals to be included in a database.

Where extensive coseismic slope failure has occurred the geotechnical response may need to be supplemented by additional volunteered geotechnical professionals that have not been previously informed of the response systems prior to the event occurring. This should not be considered a hindrance to the geotechnical response, so long as there are sufficient numbers of the response contingent who are aware of the organised procedures in the emergency response. To minimise this issue, debriefing of external geotechnical professionals should be included in the management format of the emergency response so that the incorporation of these resources is considered prior to the event occurring. The development of guidance document(s) which explain the framework for geotechnical response would improve the communication of operating procedures to geotechnical professionals with limited exposure to the response systems. A concise post-earthquake debrief outlining the response structure will also inform geotechnical professionals with limited knowledge around geotechnical response.

6.3.5 Development of data collection documents

Collection of consistent and methodical data is required during the immediate geotechnical response to support qualitative slope assessments. This could be supplemented through the use of a standard template for rapid slope assessment and data collection. A rapid safety assessment form has been developed in the *Guidelines for Building Safety Evaluation*

(NZSEE 2009) for collection of data such as the building type, location and occupancy. The assessment form also requires the inspector to notate observations made during the assessment and decisions regarding the safety of the building relative to the observations made. A similar template would be useful for post-earthquake site assessments of earthquake-induced slope failure, however, it is unlikely that the form for earthquake-induced landslide assessments could be as comprehensive as the rapid building evaluation forms. This is because it is unlikely that predefining options for the types of slope failure would assist the evaluation as there is likely to be a high variability of the types of slope failure that could occur (Chapter Two). Although definition of failure types is likely to take place in the immediate aftermath of the earthquake the hazard associated with the slope failure impact could be included in the template (i.e. inundation of material).

Due to the variability in expert judgement, the use of qualitative assessment of the risk should be noted and recorded. Where possible, it is important that qualitative assessment is explained and supported by ample reason (Crozier and Glade, 2004). For the assessment to be transferable and credible it would be useful for information contributing to qualitative assessment is adequately recorded. This also has the potential to inform further detailed assessment of the site at a later date. Table 6.3 provides suggestions for a data collection template.

To inform the database and supplement the spatial arrangement of landslide features at a site it would be useful to ensure that a notated aerial photograph or site diagram is recorded. The collection of spatial information in this manner assists the communication of observations and ensures that the information is more transferable. Along with this spatial information it would be useful to record the street location or GPS location of the site so that the information can be easily integrated into a GIS database. Timely integration of collected information into a centralised database enables maps to be developed to present the distribution of landslide features and identify and prioritise the worst hit areas.

Table 6.3: Suggested data collection for assessment forms

Information	Justification
Administration information	
Assessment location	• Identify where assessment took place
Name and contact details of geotechnical professionals involved in assessments	• Enables the assessment to be traced back to the assessor
Hazard Characterisation	
Slope failure type	• Characterisation of the slope failure to identify the associated hazards
Notes of observations (rate of failure, area affected, evacuation status of area)	
Estimate likely reactivation or type of movement (creep, rainfall, large seismic event)	• This information contributes to the analysis of slope behaviour and likelihood of failure to establish how imminent the risk is
Measurements of displacement and size of slope failure features i.e. crack aperture	
Location and type of installed slope monitoring equipment, including measurements taken	• Monitoring equipment can be easily located by other geotechnical professionals, and record of measurements is provided for further comparison
Consequence Analysis	
Diagram/sketch of slope failure and elements at risk (photographs may be attached at a later date but photo name/number could be listed)	• Provide visual information of the extent of area impacted by the slope failure or could be impacted with further failure – could allow comparison with later observations
Likely impact/consequences associated with further movement of reactivation (i.e. inundation of material on to dwelling)	• Provides analysis of the likely consequence to inform risk management decisions.
Risk Management	
Recommendations for hazard treatment and/or evacuations	• Provides a record and allows peer review of decision later in response.
Note reasons for evacuation recommendations	
Further Assessment	
Recommendations for further review of the site	• Enables record of further site assessment that may be required during the response.

6.3.6 Assemble geotechnical response resources pre-event

In the aftermath of a large scale earthquake it is often difficult to obtain the resources required to inform a geotechnical response. This issue was observed in the response to the Canterbury Earthquake Sequence particularly in regards to aerial photography and the development of a GIS database. In preparation of an earthquake, resources can be assembled to support the efficient execution of a geotechnical response. It is recommended that the following resources are obtained prior to an event:

- Maps of lifeline routes, critical buildings and infrastructure in hilly terrain,
- Aerial photographs and historical information of known slope instabilities,
- Hard copies and electronic copies of assessment forms for immediate reproduction,
- A pre-prepared contact list of details for territorial authorities, Civil Defence and Emergency Management (CDEM) contacts and Urban Search and Rescue contacts should be ready to distribute to all volunteering geotechnical professionals to reduce the requirement for contacts to form immediately post-earthquake. The prepared list should be updated regularly to ensure contact details are recent.
- A building should be identified to be used as the coordination centre for the geotechnical response. Ideally internal geotechnical group meetings will take place at the coordination centre. It would be appropriate to locate the geotechnical coordination centre within or adjacent to the CDEM Emergency Coordination Centre, Emergency Operations Centre or Building Safety Evaluation Coordination Centre so that communication can be maintained within the response.

Providing a location for meetings is crucial because they facilitate internal communication within the geotechnical response group. Ideally the geotechnical response should begin with a meeting to coordinate initial deployment. In the immediate aftermath of an earthquake information that needs to be communicated include:

- Information collected during aerial and ground reconnaissance to inform decisions around which areas should be prioritised for assessment,
- Resource requirements i.e. monitoring equipment, involvement of USAR or further geotechnical professionals,
- Accessibility issues i.e. transportation routes that have been damaged and prevent access to locations impacted by slope failures,
- Assessment teams should be briefed regarding the lines of communication, procedures, and responsibilities prior to deployment from the coordination centre.

6.3.7 Pre-earthquake geotechnical response training

Basic training in civil defence and emergency management response systems would be useful for geotechnical professionals to understand their role within existing emergency management systems. Training in the New Zealand Coordinated Incident Management System (CIMS) would provide knowledge around existing emergency management systems used by emergency services and CDEM. This will encourage understanding of role requirements, communication requirements and structure of emergency response prior to an earthquake occurring. As discussed in Chapters Four and Five, this was an issue within the geotechnical response to the 22nd February 2011 earthquake.

Basic training in public communication for geotechnical professionals in leadership roles would be useful to encourage clear and consistent communication with residents. To supplement the demand for information from residents several geotechnical experts may be required to specifically address public communication. This was observed in the Canterbury Earthquake Sequence when public communications were a large component of the geotechnical response.

6.4 Post-earthquake management of geotechnical response

Pre-earthquake preparation can include the development of management structures and data collection documents to meet the requirements for post-earthquake response, however, the following response requirements may be difficult to address through pre-earthquake planning:

- A deployment regime – deployment is typically informed through information obtained from the initial impact assessment. The development of geographic sectors to guide deployment worked well during the CES, however, information concerning the extent of area impacted was needed to inform this strategy,
- A data management platform to allow data synthesis and analysis – a pre-developed flexible geospatial platform may be difficult to maintain due to constant changes in technology.

Based on the response tasks observed during the CES, a proposed response sequence outlining the requirements for data analysis and deployment has been displayed in Figure 6.2.

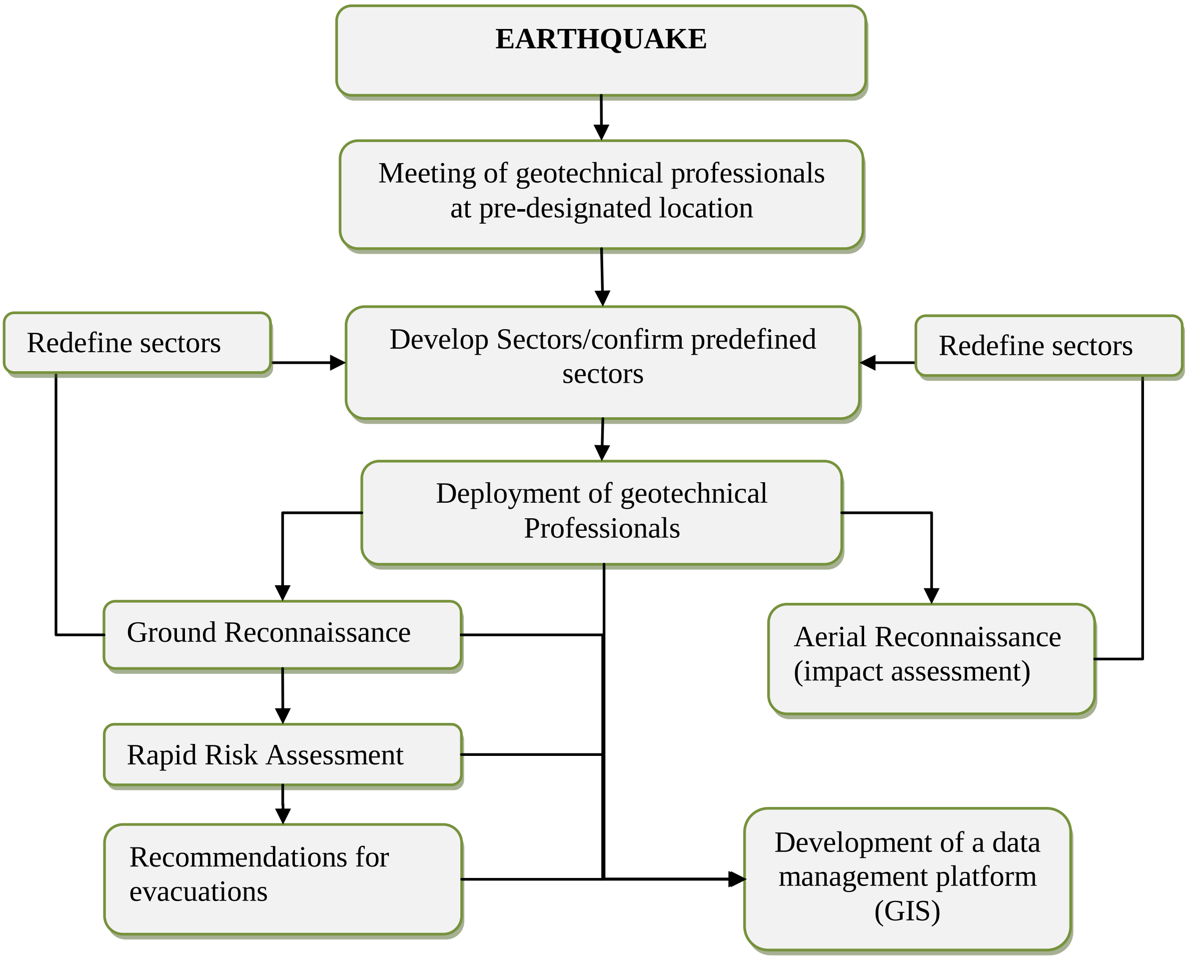


Figure 6.2: Proposed format for activation of geotechnical response

6.4.1 Development of geographic sectors within areas affected by earthquake

The development of geographic sectors within the Port Hills was a successful technique used during the CES, and has been used during the response to the 2011 Nelson floods where rainfall-induced slope failure occurred. Division of the affected area into sectors in the immediate response phase would be useful for the coordination of initial mobilisation and deployment. Information from aerial reconnaissance and ground reconnaissance should inform the development of sectors in the area affected. Factors that may influence the number of sectors required include:

- The severity of the event;
- Extent of earthquake-induced landsliding;
- Placement of vulnerable elements within the area affected; and
- Availability of response resources.

For cities or regions that are known to be susceptible to earthquake-induced landsliding it would be useful to divide the area into sectors as part of the CDEM emergency response plan. For cities such as Wellington, New Zealand, this system could be beneficial as there is a known landslide risk in this area and a known seismic hazard (Greater Wellington Regional Council 1996). For some cities this may be inappropriate or excessive if the area susceptible to coseismic slope failure is relatively minor, or areas susceptible are not extensively populated. Sectors established prior to an earthquake should remain adaptable to the extent of area impacted.

Geomorphological and geological mapping prior to an earthquake event could be used to contribute to sector division and susceptibility mapping. Susceptibility mapping contributed to the ongoing response to the 1999 Chi-Chi Earthquake and 1994 Northridge Earthquake described in Chapter Two which aided the deployment of geotechnical professionals to areas of high risk.

6.4.2 GIS database or data management platform

Analysis of the response to the CES and historical earthquakes has provided insight into the importance of a post-earthquake data management system. The benefits of utilising a data management system, such as a GIS platform, include the following:

- Spatial data analysis of hazard locations to inform emergency management decisions i.e. prioritisation of areas,
- Comparison between hazard location and the location of critical infrastructure or residential areas to inform deployment,
- Provide spatial information of areas where assessment is complete or assessment is required

A Geospatial database may be established in the aftermath of an earthquake using information obtained from local and regional authorities. The integration of historical slope failure locations or previous landslide susceptibility mapping within the data management platform may be useful to aid initial deployment. The response to the 1994 Northridge earthquake and the 1999 Chi-Chi earthquake indicated that landslide inventories and susceptibility mapping are useful for understanding the mechanical response of a slope to seismic shaking and can inform emergency responders of where to centralise response efforts in the aftermath of an earthquake or aftershock.

6.5 Summary

Case study analysis of the Canterbury Earthquake Sequence (CES) and international earthquakes (1994 Northridge, 1999 Chi-Chi and 2008 Wenchuan earthquakes) which produced significant co-seismic slope failure managed by geotechnical professionals, has provided insight into the requirements of post-earthquake geotechnical response to earthquake-induced slope failure. Information from the case study analysis indicates that the priority of the response is the protection of life safety. To address this priority the following recommendations have been made for pre-earthquake planning:

1. Develop a management structure within the geotechnical response:
2. Designate key personnel within the management structure;
3. Establish integration between CDEM and geotechnical professionals;
4. Develop a register of geotechnical professionals to resource post-earthquake response;
5. Develop a data collection document to provide consistent data collection;
6. Assemble resources prior to an earthquake;
7. Provide geotechnical professionals with training in Emergency Management principles and public communication.

Despite implementation of pre-planning the following requirements are likely to be addressed in the aftermath of an earthquake:

1. The development of geographic sectors to inform deployment within the impacted area;
2. The development of a GIS database.

Discussion around these recommendations can be used to inform the development of national guidelines for geotechnical response to earthquake-induced slope failure.

Chapter Seven: Summary, conclusions and Recommendations

7.1 Thesis scope and methodology

The purpose of this study was to evaluate the response to earthquake-induced landsliding during the Canterbury Earthquake Sequence (CES) and to inform preparation for future earthquake response. The initiating earthquake in the CES occurred on the 4th September 2011 and caused minor localised rockfall and slope failure in loess which conformed to historical slope failures recorded in the Port Hills. However, extensive slope failure induced by the 22nd February 200 earthquake was unprecedented, and ground motions experienced significantly exceeded the 500-year event in the then current probabilistic seismic hazard model for Canterbury.

Semi-structured interviews with geotechnical professionals, scientists, and representatives from local and regional authorities were conducted to collect information regarding the coordination and management of the response to earthquake-induced landsliding during the CES. Because the 22nd February 2011 earthquake was the first event in the CES to cause widespread co-seismic rockfall, cliff collapse and loess failure, rapid deployment of geotechnical professionals was required to undertake life safety risk assessments and inform on hazard management. Processes for coordinating this response developed post-earthquake because there was no pre existing framework for large-scale slope assessment during a state of emergency. Analysis of the geotechnical response to the CES indicated that the response by the geotechnical community to coseismic slope failure was well executed but would have been improved with pre-planning.

A temporal progression of response priorities, tasks and requirements was developed as a phased conceptual model based on the geotechnical response to the 22nd February 2011 earthquake. Literature review of the 1994 Northridge (California), 1999 Chi-Chi (Taiwan), and 2008 Wenchuan (China), earthquakes was conducted to allow comparison with the CES. This enabled three response phases: emergency geotechnical response (Phase One), coordinated geotechnical response (Phase Two), and Recovery (Phase Three), to be identified after each of the international earthquakes and the 22nd February 2011 earthquake.

7.2 Principal conclusion

The primary conclusion for post-earthquake geotechnical response to coseismic landslides is that development of national guidelines is required to prepare for future earthquakes. Furthermore, current building safety evaluation practice in New Zealand should incorporate geotechnical assessment alongside structural assessment, similar to section 11 of the ATC-20 guidelines for post-earthquake building safety evaluation used after the 1994 Northridge earthquake. The ATC-20 guidelines outlined the types of geotechnical hazards likely to be induced co-seismically, and provided recommendations for management of high risk hazards.

Challenges and success identified in Canterbury Earthquake Sequence (CES) have enabled comparison between the New Zealand geotechnical response methodology and international response methodologies. The absence of pre-existing guidelines for geotechnical response during the CES was the most significant difference to the 1994 Northridge and 1999 Chi-Chi earthquakes, which were both guided by pre-event preparation which informed response and management strategies for geotechnical hazards. Pre-earthquake planning in these two cases enabled early implementation of a coordinated slope assessment post-earthquake, and in the case of Northridge informed transparent integration between building safety evaluation and assessment of geotechnical hazard.

Examination of the 22nd February 2011 earthquake indicated that challenges in the response to earthquake-induced landsliding in the Port Hills arose primarily from the lack of integration of geotechnical hazards into Civil Defence and Emergency Management response strategies. Furthermore, deficiencies in consistency of slope assessment and deployment of resources hindered an efficient execution of response capabilities in the first two weeks post-earthquake. These challenges were addressed through the development of management strategies within the geotechnical response group during the first two weeks post-earthquake.

Despite New Zealand's history of earthquake-induced landsliding (Hancox et al. 2002) the CES was the first to induce widespread slope failure in an urban area. Several other major cities in New Zealand, such as Wellington, Dunedin and Nelson, are situated on terrain similar to that of the Port Hills and consequently have the potential to exhibit similar coseismic slope failure. As such, the experience of the CES indicates that it is imperative that guidelines for geotechnical response to earthquake-induced landsliding are developed. To inform further planning of post-earthquake geotechnical response, a series of recommendations have been developed based on the CES case study analysis with comparison to historical earthquakes.

7.3 Recommendations

Recommendations to inform future guidelines were developed based on the case study analysis of the CES and historical international earthquakes which provided insight into the requirements for response to earthquake-induced landsliding. Recommendations include:

<u>Pre-earthquake preparation</u>

1. Integrate geotechnical response with Civil Defence and Emergency Management (CDEM) to ensure management of earthquake-induced landslides is incorporated within wider emergency management systems.
2. Develop an adaptable management structure for geotechnical response pre-earthquake, including a hierarchical framework for roles within the response group.
3. Designate significant roles within the geotechnical response framework pre-earthquake in anticipation of geotechnical response.
4. Prepare a register of geotechnical professionals pre-earthquake who are capable of assisting in rapid post-earthquake geotechnical response.
5. Response resources, such as maps of critical infrastructure, lifeline routes or areas of historic landslide movement, should be gathered pre-earthquake so that information is readily available.
6. A standard data collection sheet capable of site specific adaption should be developed pre-earthquake to improve consistency in data collection and slope assessments in various terrains.
7. Geotechnical professionals involved in geotechnical response should undertake basic Civil Defence and Emergency Management training, such as familiarity with Coordinated Incident Management System (CIMS).
8. Training in public communication should be made available to geotechnical professionals who are likely to be involved in leadership roles in the response.

Post-earthquake management recommendations

1. Geographic sectors of the area affected by earthquake-induced landslides should be distinguished as part of the post-earthquake response management to ensure all areas affected by coseismic landslides are incorporated into the response.
2. A GIS database should be established immediately post-earthquake for timely data management and analysis.

Based on these recommendations, further work will be required to develop these recommendations into national guidelines for post-earthquake geotechnical response. The success of these guidelines will require the commitment of government level organisations and professional groups to contribute and agree on the development of sustainable and practical methods for geotechnical response. Furthermore, pre-earthquake planning must remain adaptable to a variety of earthquake scenarios and terrains, and support a flexible management system for a range of landslide types.

7.4 Further work

The analysis of post-earthquake geotechnical response to earthquake-induced slope failure during the CES has highlighted the need for pre-earthquake planning. The aim of this thesis has been to inform the development of national guidelines or guidance notes around post-earthquake geotechnical response. To support this outcome, further research is necessary in the following areas:

- Further research to inform the integration of response to liquefaction and lateral spreading into the post-earthquake geotechnical response to earthquake-induced slope failures which a separate series of mechanisms geotechncially.
- Further research to establish specific techniques for emergency response to various failure mechanisms, including scenario developments to inform CDEM response.
- Further research and review of additional historical earthquakes case studies to supplement current understanding of geotechnical response conducted internationally. Review of historical earthquakes in this thesis was limited to published literature; it would be useful to review post-earthquake reports specifically developed for government organisations that may have not been published.

- Further interviews with local, regional, and national government to research the influence of legislation and current emergency management strategies on the development of geotechnical guidelines, particularly in the involvement of building safety evaluation formats and their adaption to include geotechnical aspects.
- Conduct further interviews to gauge the willingness of the geotechnical community, CDEM and local and national government to implement response preparation through development of response guidelines.
- Conduct further interviews with Urban Search and Rescue (USAR) to inform the development of strategies to incorporate the capabilities of USAR into national guidelines for post-earthquake geotechnical response.

This thesis and further research will inform the development of national guidelines for geotechnical response to earthquake-induced slope failure, and ensure that New Zealand follows international best practice.

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Appendix A – Landslide hazard characterisation

The term landslide is broadly defined as "the movement of a mass of rock, debris or earth down a slope" (Cruden and Varnes 1996). The term can be used to describe a wide range of phenomena which can occur in various materials, vary in scale, and type and rate of movement (Hincks et al. 2013). Landslide classification is important because it is one of the first steps of hazard analysis in the assessment and management of landslide hazard and risk. Landslides are typically classed according to the mode of failure and the type of material undergoing movement. Classification systems have been discussed by Hutchinson (1988); Crozier (1989); Cruden and Varnes (1996); Dikau and European Commission (1996). The classification system outlined by Cruden and Varnes, (Table A.7.1) is a commonly used for landslide characterisation and has been used in world-wide research of earthquake-induced slope failure (Keefer 1984; Rodriguez et al. 1999).

Table A.7.1: Cruden and Varnes (1996) clasification of slope movements. Fine material is defined as >80% of material is comprised of particles smaller than 2mm

		Material		
			Engineering Soils	
Movement		Bedrock	Coarse	Fine
Fall		Rock fall	Debris Fall	Earth Fall
Topple		Rock Topple	Debris topple	Earth topple
Slide	Rotational Translational	Rock Slump, block slide, slide	Debris slump, block slide, slide	Earth slump, block slide, slide
Lateral Spread		Rock Spread	Debris Spread	Earth spread
Flow		Rock flow (deep creep)	Debris flow	Earth flow
			Soil Creep	
Complex		Combination of two of more principle types of movement		

The rate of failure is also used to classify landslides. The landslide velocity scale proposed by Cruden and Varnes (1996), Table A.7.2, is a widely used velocity classification system that presents a correlation between the movement velocity and a description of the rate of movement. Assessment of the rate of movement is important because the velocity of a landslide affects the impact potential and consequently affects landslide risk management techniques (Crozier and Glade 2004).

Table A.7.2: Classification of velocity of movement according to Cruden and Varnes (1996)

Velocity Class	Description	Velocity (mm/s)	Typical Velocity
7	Extremely Fast		
		5×10^{3}	5 m/s
6	Very Fast		
		5×10^{1}	3 m/min
5	Fast		
		5×10^{-1}	1.8 m/hr
4	Moderate		
		5×10^{-3}	13 m/month
3	Slow		
		5×10^{-5}	1.6 m/year
2	Very Slow		
		5×10^{-7}	16 mm/year
1	Extremely Slow		

A review of worldwide studies of earthquake-induced slope failure undertaken by Keefer (1984) and Rodriguez et al. (1999) has been used to collate characteristics of coseismic landslides with typical landslide classification principles outlined by Cruden and Varnes (1996) (Table A.7.3). Based on reviewed literature, Table A.7.3 provides a synthesis of proposed thresholds for slope angle, minimum shaking intensity, and minimum magnitude events required to induce each type of landslide. Characterisation of earthquake-induced landslides to determine such thresholds can contribute to hazard and risk analysis and management. Information from research into New Zealand earthquake-induced landsliding by Hancox et al. (2002) has been included to provide local comparison of landslide characteristics. Site specific variability in material composition, local ground water conditions, pre-earthquake static slope stability, additional trigger events (e.g. rainfall prior to earthquake occurring), and influence from peak ground acceleration are some of the limiting factors that have not been appreciated in these thresholds and are limitations to the generic application of these characteristics.

Review of the classification system used by Keefer (1984) and Rodriguez et al. (1999) in Table A.7.3 highlights the distinction between disrupted and coherent slides and falls used for characterisation of earthquake-induced landslides. This distinguishes an additional development in classification of earthquake-induced slope failure in comparison to typical landslide classification outlined by Cruden and Varnes (1996). According to Keefer (1984) disrupted landslides refer to a material not moving as a coherent mass. Disturbance of 'disrupted' material occurs when it is released from the slope, as such most mass movements of material will have some degree of internal disruption (Keefer 2002).

Table A.7.3: Characteristics of earthquake-induced landslides (Modified from Keefer 1984; Keefer 2002)

Name	Type of Movement	Typical Material type	Slope angle threshold	Minimum Shaking Intensity	Minimum Magnitude Earthquake
LANDSLIDES IN ROCK					
Disrupted slides and Falls					
Rockfall	• Bouncing, rolling, free fall (Keefer 1994; Cruden and Varnes 1996; Keefer 2002; Massey et al. 2012a) • Descends very rapidly to extremely rapidly (>5m/sec) and travels in unpredictable path down slope (Massey et al. 2012a)	• Individual block of rock or small number of boulders (Keefer 1984) • Fractured or weakly cemented rock slopes with a wide range of rock types (Keefer 1984; Rodriguez et al. 1999) • Depth of failure dependant on spacing of discontinuities (Rodriguez et al. 1999)	>40° (Keefer 1984; Keefer 2002) >40° (Hancox et al. 2002)	MMI IV (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=4.0 (Keefer 1984) M_L=5.5, M_S = 5.4 (Rodriguez et al. 1999)
Rockslide	• Translational sliding (Keefer 1984; Cruden and Varnes 1996; Rodriguez et al. 1999; Keefer 2002) • Slide refers to down slope movement of material on planar or curved dominant failure surface such as a shear zone, bedding plane or other discontinuity dipping out of slope (Cruden and Varnes 1996) • Can occur as shallow or deep movement (between 3-100m) (Rodriguez et al. 1999)	• Mass of rock which have been disordered during movement into fragments and blocks. Materials variable however typically failure occurs on shear surface or outward dipping discontinuity or plane of weakness (Keefer 1984) • Preferential poorly cemented sedimentary material (Rodriguez et al. 1999)	> 35° (Keefer 1984; Keefer 2002) >55° (Rodriguez et al. 1999) >25°-35° (Hancox et al. 2002)	MMI IV (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=4.0 (Keefer 1984) M_L=5.5, M_S = 5.4 (Rodriguez et al. 1999)
Rock avalanche	• Sliding and/or flow movement with occasional free fall (Keefer 1984; Keefer 2002) • Rock avalanches can travel several kilometres at high velocities usually greater than 3m/sec (Keefer 1984).	• Highly disrupted and fragmented rock that moves as stream of rock fragments (Keefer 1984)	> 25° (Keefer 1984; Hancox et al. 2002; Keefer 2002) Source area >150m high (Keefer 1984)	MMI IV (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_S=6.0 (Keefer 1984) M_S = 6.5 (Rodriguez et al. 1999)
Coherent Slides					
Rock slumps	• Rotational sliding. Sliding typically on basal shear surface with component of head ward rotation (Keefer 1984; Keefer 2002) • Keefer 1984 suggested movement was typically slow to rapid (0.3m/sec - 1.5m/yr) on Varnes landslide movement scale (Varnes 1978)	• Variable rock types. Often weak rock, poorly cemented, closely jointed, weathered or sheared rock (Keefer 1984)	>15° (Keefer 1984; Keefer 2002)	MMI V (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=5.0 (Keefer 1984) M_L=6.5, M_S = 5.9 (Rodriguez et al. 1999)
Rock block slides	• Translational sliding movement on basal shear surface or discontinuity dipping out of slope, minimal rotational movement (Keefer 1984). • Depth of slide controlled by geological features or plains of weakness in rock mass (Rodriguez et al. 1999).	• Variable material where basal shear surface is present (Keefer 1984) • Typical materials can include: tuff, andesite, weakly cemented pumice, closely jointed or weakly cemented shale, sandstone, siltstone, mudstone (Keefer 1984) • Volcanic deposits such as tuff, pumice tephra, basalt; also sedimentary and metamorphic deposits (Rodriguez et al. 1999) • Weakening of soil material may also be attributed to contributing factors such as a high water table which could cause saturation at the failure surface	>15° (Rodriguez et al. 1999) >15° (Keefer 1984; Keefer 2002) >15° (Hancox et al. 2002)	MMI V (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=5.0 (Keefer 1984) M_L=6.5, M_S = 5.9 (Rodriguez et al. 1999)
LANDSLIDES IN SOIL					
Disrupted slides and Falls					
Soil Falls	• Free fall, rolling, bounding (Keefer 1984; Keefer 2002) • Typically mass may disintegrate upon decent and impact, consequently run out length may be less than rockfall (Keefer 1984)	• Block or disrupted mass of soil (Keefer 1984)	>63° measured, >40° predicted (Keefer 1984; Keefer 2002)	MMI IV (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=4.0 (Keefer 1984) M_L=5.5, M_S = 5.4 (Rodriguez et al. 1999)
Disrupted soil slides	• Translational slide (Keefer 1984; Cruden and Varnes 1996; Keefer 2002) • See slide definition in "rockslides"	• Variable materials that move on soil-bedrock contacts or boundaries between soil layers, typically loose, unsaturated residual or colluvial sand (Keefer 1984)	>15° (Keefer 1984; Keefer 2002)	MMI IV (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=4.0 (Keefer 1984) M_L=5.5, M_S = 5.4 (Rodriguez et al. 1999)

Soil Avalanches	• Complex, involving translational sliding with subsidiary flow, and occasional free fall (Keefer 1984; Keefer 2002)	• Disintegrated, disrupted soil. Soil avalanche consists of streams of grains and small blocks of soils (Keefer 1984)	>25° (Keefer 1984; Keefer 2002)	MMI IV (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_S=6.5 (Keefer 1984) M_S = 6.0 (Rodriguez et al. 1999)
Coherent Slides					
Soil Slumps	• Rotational sliding on basal shear surface (Keefer 1984; Keefer 2002). • Keefer 1984 suggested movement was typically slow to rapid (0.3m/sec - 1.5m/yr) on Varnes landslide movement scale (Varnes 1978)	• Materials variable, including manmade fill, flood-plain alluvium (Keefer 1984)	>7° (Keefer 1984; Keefer 2002)	MMI V (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=4.5 (Keefer 1984) M_L=5.5, M_S = 5.4 (Rodriguez et al. 1999)
Soil block slides	• Translational sliding, minimal rotational movement (Keefer 1984; Keefer 2002)	• Materials variable, including manmade fill, flood-plain alluvium most commonly (Keefer 1984) • Weakening of soil material may also be attributed to contributing factors such as a high water table which could cause saturation at the failure surface	>5° (Keefer 1984; Keefer 2002)	MMI V (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=4.5 (Keefer 1984) M_L=5.5, M_S = 5.4 (Rodriguez et al. 1999)
Slow earth flows	• Translational sliding on saturated basal shear surface with minor internal flow (Keefer 1984; Keefer 2002)	• Materials variable, including clayey residual soil, clayey loam, till, volcanic ash, colluviums. Typically can occur where basal shear surface is saturated (Keefer 1984)	>10° (Keefer 1984; Keefer 2002) >10° (Hancox et al. 2002)	MMI V (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=5.0 (Keefer 1984) M_L=6.5, M_S = 5.9 (Rodriguez et al. 1999)
Lateral Spreads and Flows					
Soil lateral spreads	• Translation on basal zone of liquefied gravel, sand or silt or weakened sensitive clay (Keefer 1984).	• Materials variable, including alluvium and manmade fill primarily (Keefer 1984)	>0.3° (Keefer 1984; Keefer 2002)	MMI V (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=5.0 (Keefer 1984) M_L=6.5, M_S = 5.9 (Rodriguez et al. 1999)
Rapid soil flows	• Flow similar to a liquid and at high velocities(Keefer 1984)	• Stream of soil grains, usually but not always mixed with water (Keefer 2002)	>2.3 (Keefer 1984; Keefer 2002)	MMI V (Keefer 1984) MMI V (Rodriguez et al. 1999)	M_L=5.0 (Keefer 1984) M_L=6.5, M_S = 5.9 (Rodriguez et al. 1999)

Appendix B – Manuscript for New Zealand Geotechnical Society Conference, 2013

This appendix presents a paper that was presented at the New Zealand Geotechnical Society Conference in Queenstown, New Zealand, November 2013. The manuscript details the research methodology as at May 2013. The principle difference between the research methodology in the manuscript, and the research methodology in Chapter Two of this thesis, is the examination of four case study slope failure sites in the Port Hills, Christchurch that was not included in the final research due to confidentiality requirements from Christchurch City Council.

Geotechnical Risk Assessment of hilly terrain during post-earthquake response

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Keywords: Canterbury Earthquakes, risk assessment, geotechnical, guidelines, landslides

ABSTRACT

The 2010-2012 Canterbury Earthquake sequence has highlighted and identified the value of standardised, practical and co-ordinated guidelines for geotechnical risk assessment for inhabited areas in the aftermath of a natural disaster. The lack of guidelines and provisions to manage the assessment of geotechnical hazards hindered co-ordinated, timely and transparent management of geotechnical risk in the hilly suburbs of Christchurch.

The earthquake sequence triggered rockfall, landslide and cliff collapse events throughout the Port Hills. This damaged thousands of houses and critical infrastructure, and created a life risk issue for people inhabiting the area. Given the high seismic hazard in New Zealand and the location of significant active faults near populated centres, it is beneficial to learn from the response undertaken following the Christchurch Earthquake sequence to inform geotechnical risk assessment guidelines for future events.

This paper examines our proposal for research into how the geotechnical risk assessment approach evolved throughout the earthquake sequence and in the apparent post-sequence period. This research will aim to establish the evolution of information needed as the response progressed, and identification of lessons learnt. The basis for geotechnical risk assessment guidelines has been derived from the analysis of experiences from key municipal, management and operational stakeholders who were involved in the geotechnical risk assessment during the Canterbury earthquake sequence.

1 INTRODUCTION

The Christchurch Earthquake sequence that initiated on the 4th September 2010 has been a learning curve for most geotechnical professionals involved in the post earthquake response. Over the past 70 years, New Zealand has had limited exposure to widespread earthquake induced slope failure in largely urbanised and populated areas such as the Port Hills, Christchurch. Because of this, the majority of the response and risk assessment methodologies were developed reactively after the 22nd February 2011 earthquake. Geotechnical Engineers and Engineering Geologists were deployed to areas of Christchurch to assess the landscape response and subsequent damage to slopes from the earthquake sequence. This assessment of the landscape led Geotechnical Engineers and Engineering Geologists to then examine the risk to life safety of residents exposed to slope failures induced by the earthquake sequence. The lack of guidelines for assessing this risk hindered a co-ordinated and timely response. Because of this it became clear that it would be beneficial to New Zealand to have a framework which outlines how to respond to earthquake induced slope failures.

New Zealand has a high level of earthquake risk due to a number of highly active faults that feature throughout the country. This partnered with growing urbanisation in areas of steep terrain can present a life risk issue from earthquake induced slope failures. Since 1840 there have been at least 22 recorded earthquakes in various locations through New Zealand that have resulted in widespread earthquake induced landsliding (Hancox et al 2002). Examples include the 1929 Murchison earthquake and the 1968 Inangahua earthquake which resulted in some loss of life from extensive landsliding induced by ground shaking. However, most of the 22 earthquakes have occurred in sparsely populated areas, minimising loss of life and damage to infrastructure. Because of this, the experiences, management strategies and lessons learnt by those responding to slope failures induced by the Canterbury earthquake sequence offer a rare, valuable and perishable opportunity for documentation of this information in order to prepare for future earthquake events. Ideally, the systematic investigation and documentation of these lessons will provide a foundation for New Zealand to develop a planned response in the form of guidelines for future earthquake events.

This paper outlines a methodology proposed for developing guidelines for geotechnical risk assessment in the aftermath of an earthquake. The development of these guidelines is primarily focussed on the response and management systems that originated and were refined during the Christchurch earthquake sequence. Details of the Christchurch earthquake sequence and the response to the earthquake sequence will be presented as a case study to support the development of such guidelines. The use of terminology in this paper is consistent with ISSMGE Glossary of Risk Assessment Terms (listed on TC304 web page: http://140.112.12.21/issmge/2004Glossary_Draft1.pdf) where "risk" is described as the measure of the probability and severity of an adverse effect to life, health, property or environment.

2 METHODOLOGY FOR THE DEVELOPMENT OF GUIDELINES FOR GEOTECHNICAL RISK ASSESSMENT

As part of the proposed research methodology, guidelines for post earthquake geotechnical risk assessment will be developed through examination of a combination of response techniques from an international and a local level that addresses the geotechnical issues particular to New Zealand. The proposed research has been divided into two phases, currently the first phase of the research has been completed and the second research phase is due to commence. The first phase of the research aimed to examine the response systems performed by other countries during international earthquakes which have induced slope failure. During the second phase, geotechnical experts who responded to the Christchurch earthquake sequence will be interviewed in an effort to record the local level response methods and lessons learnt from the Christchurch earthquake sequence. Information gathered during these two phases of research will be used to make recommendations for guidelines for geotechnical risk assessment.

2.1 Phase One -Review of international case-studies

At an international level, methods of geotechnical response used during the 1994 Northridge earthquake, the 1999 Chi-Chi earthquake and the 2008 Wenchuan earthquake have been identified to show an outline of practised response methodologies. Review of published literature was used to identify relevant information from these international events. The individual aspects of response identified provide suggestions for typical components of geotechnical response. The majority of these methods are comparable to the geotechnical response to the Christchurch earthquake and are therefore applicable to the New Zealand context.

2.2 Phase Two - Analysis of the geotechnical response on the Port Hills during and following the Canterbury earthquake sequence

At a local level, review of the response to earthquake-induced slope failure in the Port Hills during the Christchurch earthquake sequence has been helpful for understanding how geotechnical response developed in New Zealand. This information has been obtained through a series of interviews with key municipal, management and geotechnical experts who participated in the response to earthquake induced slope failure initiated by the Christchurch earthquake sequence. This approach has been taken because little information regarding the mechanisms of response has been recorded since the earthquake sequence commenced. It would be useful to collaborate experiences and lessons learnt from these individuals who responded in order to prepare for future events.

As part of the proposed research, participants involved in the interview process will be divided into three groups: strategic level response, tactical level response and case study participants (Figure 1). Tactical level response refers to the geotechnical engineers or engineering geologists who were involved in observing and assessing slope failures and making decisions about the associated risk on site. Strategic level response refers to the management operatives who were involved in making large scale decisions and took part in organising and managing the overarching approach to geotechnical risk assessment. In some cases individual participants can be categorised in to both or neither of these roles, and in this circumstance the question set was tailored to their specific role.

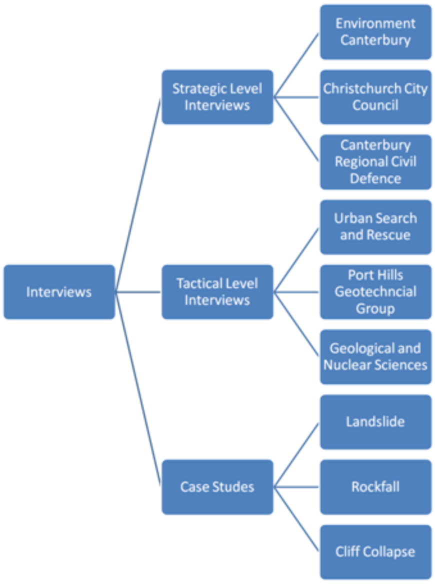

Figure 1 - Framework for interviews

Up to four case study sites will be examined to gain an understanding of the requirements of geotechnical response for site specific failure mechanisms. This will be achieved by interviewing the tactical level geotechnical experts who responded to each of the sites. The question set will focus on the failure mechanisms and geotechnical response efforts for each of the sites. Methods of practically assessing the geotechnical risk in post earthquake environment will be identified from interviewing participants from the tactical response group and the case study level group. This will form the basis of 'on the ground' response methodologies in the guidelines for geotechnical risk assessment.

Interviews with strategic level participants will seek to shed light on the management of geotechnical response which developed after the 22nd February 2011 earthquake. This is important for identifying what information is required for finalisation of higher level decisions such as zones of evacuation. These interviews will also focus on the reporting system that developed within management level organisations during the response to earthquake induced slope failure. Interviews will be semi-structured and will be guided by a question set. Additional questions may be added throughout the interview to follow up and explore key statements and themes conveyed by the participants. Participants will be asked questions that aim to walk them thought the disaster sequence from the 4th September 2010 to December 2011. Depending on their level of involvement this timeframe may be shortened.

A representative timeline of key events during this period will be presented to each of the participants to act as a visual aid to prompt memories and experiences during that time. Key events include government level decisions such as states of emergency and introduction of legislation regarding the Christchurch earthquake sequence. Large rainfall and snowfall events have also been included because these had the potential to affect the geotechnical response. Participants will also be presented with a topographic map of the Port Hills as a spatial aid to discern where in the area they were active during the response.

These tactical, strategic and case study level interviews will highlight which approaches hindered and which aided a timely and coordinated response in the initial days to weeks after the 22nd February 2011 earthquake. These will be combined with successful response approaches used in international examples to generate guidelines for geotechnical risk assessment in a post-earthquake environment.

3 INTERNATIONAL CASE STUDIES FOR GUIDELINE DEVELOPMENT AND RESEARCH

Analysis of international case studies such as the 1994 Northridge earthquake, the 1999 Chi-Chi earthquake and the 2008 Wenchuan earthquake has been useful for identifying components and organisational aspects of response used internationally. For example, during the 1999 Chi-Chi earthquake the seismic hazard was managed by a collaboration of several government level organisations and the mobilisation of engineers and scientists who undertook ground reconnaissance. Technical support and information and data management was divided between two national science organisations with the National Science Council acting as the over-arching organisation responsible for the management of seismic hazard (Loh & Tsay 2001). This organised approach to disaster response enabled a systematic post earthquake reconnaissance of earthquake induced hazards.

After the 1994 Northridge earthquake in California as part of the response plan government level organisations collected and analysed reconnaissance information commencing hours after the earthquake (USGS 1996). Using this information, probabilistic seismic landslide hazard maps and spatial mapping of earthquake induced landslides enabled a growth of knowledge regarding the susceptibility of slopes in the area to failure (Jibson et al 2000, Parise & Jibson 2000). This research has enabled geotechnical experts in California to learn from the event by the identification of higher risk areas that are likely to fail again from further seismic events. This could aid post-disaster decisions such as the deployment of geotechnical experts because areas that are likely to have failed can be easily located.

4 THE CHRISTCHURCH EARTHQUAKE SEQUENCE AS A CASE STUDY FOR GUIDELINE DEVELOPMENT AND RESEARCH

The initial earthquake in the Christchurch earthquake sequence (M_W 7.1) took place at 4:35am on the 4th September 2010. The earthquake initiated from rupture on the previously unknown Greendale fault, southwest of the city (Berryman 2012). Although there was no loss of life and widespread damage in the Central Business District (CBD), the earthquake caused only minor rockfall in the Port Hills. Less than 6 months after the first earthquake a smaller earthquake (M_W 6.2) ruptured at 12:51pm on the 22nd February 2011. The earthquake was located on the Christchurch fault directly southeast of the city and caused the loss of 185 lives, damage to infrastructure, life lines and residential areas (Berryman 2012).

Extensive earthquake induced slope failure was initiated in the Port Hills by the 22nd February earthquake. These features were widespread in the hilly suburbs and were responsible for the loss of five lives. Earthquake induced landslides became an umbrella term for four categories of slope failure: rockfall, cliff collapse, landslides and retaining wall failure. From accelerometers located near the Port Hills measured peak ground accelerations (PGA) in the vertical direction reached up to 2.21g, while PGA in the horizontal direction reached 1.41g at Heathcote Valley Primary School (Wood et al 2011). Scientists have attributed the strong ground shaking felt in the Port Hills area to these high PGA values. This is likely to have been the cause for the extent of geotechnical failure in the Port Hills (Massey et al 2012b). Following the 22nd February earthquakes several large aftershocks triggered further slope failure in the Port Hills. These included earthquakes on the 13th June 2011 (M_w 6.0) and 23rd December 2011 (M_w 5.9). The worst of these was the 13th June 2011 earthquake which initiated similar maximum horizontal peak ground accelerations to that of the 22nd February 2011 earthquake (Berryman 2012). Further slope failure from these earthquakes required many sites to be re-evaluated by geotechnical experts.

4.1 Response to earthquake induced slope failures in the Port Hills

Understanding the geotechnical response to the Christchurch Earthquake sequence is important for the development of guidelines for New Zealand as it presents a recent example of geotechnical risk management. At the current stage in the research, the response to earthquake induced slope failures in the Port Hills can be divided up into four components: Organisation and mobilisation, slope failure assessment and evacuation, monitoring, and mitigation. The response to the 22nd February 2011 earthquake in particular is likely to form the majority of the information for guidelines for geotechnical risk assessment primarily because it was the most significant event in the sequence for the development of the response. The geotechnical response to life safety risk was significant after the 22nd February 2011 earthquake because it was the first earthquake in the sequence to cause extensive slope failure in urban areas.

4.1.1 Organisation and Mobilisation

The majority of the response after the 4th September 2010 earthquake was organised by local council. This included minor rockfall induced by the earthquake that was cleaned up by local contractors. Because earthquake induced slope failure was minor there was no need for an extensive organised geotechnical response.

Hours after the 22nd February 2011 earthquake geotechnical experts responded to the situation often by their own self-mobilisation or mobilisation by their employer, rather than as a coordinated response initiated by a pre-formed national response framework. Days after the 22nd February 2011 earthquake geotechnical experts responding to the earthquake began meeting together. This aided the development of organised deployment of geotechnical experts in the Port Hills. Because this was still in the developmental stages days after the earthquake some sites were still assessed several times by multiple geotechnical response teams. Within days after the 22nd February 2011 earthquake, as more geotechnical experts became involved the Port Hills Geotechnical Group formed. The Port Hills area was divided up into several sectors which were then assigned to various geotechnical engineering companies or research institutes within the group.

4.1.2 Slope failure Assessment and Evacuation

Evacuation of properties commenced hours after the 22nd February 2011 earthquake and continued months to year after the event. As geotechnical experts assessed the slope failures mandatory evacuation was enforced for properties that could be exposed to inundation by further boulder release or cliff collapse, or could be damaged from further ground deformation from tensile cracking or compression features (Dellow et al 2011). Often the basis of the evacuation decisions was formed from information collected by geotechnical experts assessing the evidence for slope failures that had or could affect a property; however, the final decisions to enforce evacuations were made by the Urban Search and Rescue (USAR) contingent. Days to weeks after the 22nd February earthquake empirical data from field mapping became available. This enhanced the assessment of risk for particular areas where data had been collected (Dellow et al 2011).

4.1.3 Slope Monitoring

Within days of the 22nd February 2011 earthquake, evaluation of slope failures induced by the earthquake consisted mainly of visual observations of the features of each failure mechanism.

Visual inspections of cracks for both landslide and cliff collapse failures were important to understand the mechanics of movement. Measurements of crack widths were taken regularly to monitor rates of movement. Rockfall that had been located in residential areas was often traced back to the source area. The rock mass of the source area was examined visually to identify loose material that could be released by subsequent aftershocks.

Monitoring systems were installed on landslides that were identified immediately after the earthquake. Days after the 22^{nd} February 2011 earthquake these monitoring systems mainly consisted of string lines and pins installed across cracks at the head-scarp of the landslide. As equipment became available continuous global positioning systems (cGPS) and strong motion instruments were installed. Many of these devices are still in use in order to gather further information regarding slope movements. Approximately two weeks after the 22^{nd} February 2011 earthquake terrestrial light detecting and ranging (LIDAR) data was used to analyse cliff faces and identify areas of loose material (Massey et al 2012). This was used to calculate the volume of mass released from a cliff face during aftershocks and establish the movement patterns of the slope failures (Dellow et al 2011). Generally slope movements were either initiated from aftershock activity, or were creeping continuously. The nature of the landslide movements could also be observed by the deformation of buildings which straddled tension cracks or compression features (Dellow et al 2011).

4.1.4 Mitigation

Days after the 22^{nd} February 2011 earthquake evacuation was the most common form of mitigation against rockfall and cliff collapse until other measures could be achieved. Mitigation of the effects of cliff collapse included the installation of barriers such as ballasted containers along the base of the cliff to limit the extent at which the material could travel. Loose material was removed from slopes to mitigate the risk of inundation via further cliff collapse or rockfall.

5 DEVELOPMENT OF GUIDELINES FOR GEOTECHNICAL RISK ASSESSMENT

Developing guidelines for geotechnical risk assessment enables New Zealand to move forward and prepare for future earthquake events. Because New Zealand is such a seismically active country with a history of earthquake induced slope failure it is likely that a similar large-scale earthquake event could occur in a highly populated area with similar resulting geotechnical hazards. Capturing lessons learnt from the Christchurch earthquake sequence will assist in identification of response to earthquake induced slope failures and in developing a methodology for effective response. This will ensure that geotechnical experts involved in future response will have the tools necessary to undertake geotechnical risk assessment.

The development of guidelines will standardise the approach taken to risk assessment and ensure that all tactical and strategic level personnel have a consistent response to the situation. This will ensure that assessments of geotechnical hazards completed during the response phase will be uniform and comparable. Having a framework in place will enable a coordinated response by which the geotechnical hazard can be assessed more efficiently and life risk issues can be addressed promptly. Achieving coordination between response teams will eliminate or reduce communication frustrations and ensure timely analysis and processing of data. This should also minimise the amount of 'lost time' in effort to coordinate the response and enable a more timely mitigation of slope failures.

Guidelines for post disaster geotechnical risk assessment will be developed as a series of recommendations aimed at advising the geotechnical community and government level organisations. These recommendations will aim to illustrate methods for the management and practice of assessment of geotechnical risk in a post disaster context. Recommendations will be developed from processes and information needs that were reflected upon during the interview process. Examples of historical earthquake events will be used to guide and support these recommendations.

Guidelines will be initially divided into management or organisational recommendations and tactical level recommendations. Management level recommendations will refer to key operational aspects of geotechnical risk assessment such as critical path communication between organisations involved. Within this division of the guidelines it would also be helpful to develop a schematic framework of the responsibilities, interaction and requirements of and between each organisation active during the post-disaster response period. This would include government and municipal organisations, geotechnical organisations and research institutes. It would be useful within this framework to outline the information needs for each organisation to participate in the response.

Tactical level recommendations will refer to key aspects of geotechnical risk assessment that provide the fundamental analysis of risk associated with earthquake induced slope failure. Key aspects of tactical level recommendations should include logistical requirements for reconnaissance work, data documentation and analysis, methods for assessing earthquake induced slope failures, and spatial distribution of geotechnical experts. The focus of this tactical division of the guidelines will be to emphasise practical methods for assessing geotechnical risk "on the ground" and then progress to recommendations for centralisation of data and information collected during reconnaissance work.

Logistical requirements during reconnaissance should include a framework for reporting observations and analysis. In addition to this it would be prudent to suggest the use of a pro forma to be used as a method for ensuring consistency of assessing earthquake induced slope failures. Centralisation of data immediately after the earthquake will enable processing of information to commence soon after it is recorded. It would also be useful for providing organisations involved in the response with information collated from ground reconnaissance.

Tactical recommendations could also encompass suggestions for data analysis. This initially will be derived mainly from examples of data analysis from international earthquake events such as the 1999 Chi-Chi, Taiwan earthquake, and the 1994 Northridge earthquake in California. After both of these earthquakes data such as ground motion information and landslide location information was displayed spatially in order to present a visual representation of the distribution of these two data sets. Similar spatial analysis was also undertaken during the Christchurch earthquake sequence.

It will also be an important part of the guideline development to suggest relevant skill criteria and training requirements for geotechnical experts who are involved in the post disaster geotechnical risk assessment process. This is important because for the risk to be assessed adequately the assessor must exhibit competence in the geotechnical field. It is likely that this recommendation of skill criteria will be one of the founding components of the guidelines.

It is also likely that recommendations for pre-earthquake components of geotechnical risk assessment will be included in the guidelines. This is likely to include suggestions for slope stability analysis and identification of slopes with potential risk of failure triggered by earthquakes. This information regarding the stability of slopes would be useful particularly for hilly areas that are urbanised or populated. Prior knowledge of slope stability would enable geotechnical experts to assess slopes with a background knowledge regarding the risk of failure. It is possible that this information would also be useful for distinguishing which areas post-earthquake will have experienced the most slope failure and which areas are required to be examined first by geotechnical experts.

6 CONCLUSIONS

The Christchurch earthquake sequence has highlighted the need for guidelines for risk assessment of seismically induced slope failures. As part of ongoing research, guidelines will be developed from documentation of experiences and events that took place in the aftermath of the Christchurch earthquake sequence. This information will be captured from a series of tactical, strategic and case study level interviews with geotechnical experts who were involved in the response.

Because New Zealand is a seismically active country and has a history of earthquake induced slope failures, it is important that as a country we learn from the Christchurch earthquake sequence so that preparation can be made for future inevitable events.

7 ACKNOWLEDGMENTS

We would like to acknowledge the involvement of those who took the time to contribute to this study. We are also grateful for the support that Environment Canterbury and Opus International Consultants have provided for this project.

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Appendix C – Visual resources for interviews

Visual resources used for research interviews include:

- C1 Two year timeline commencing September 2010 to September 2012
- C2 Ten week timeline commencing February 2011 to April 2011
- C3 Two week timeline commencing February 2011
- C4 Topographic map of Port Hills, Christchurch

Information included on the visual timelines was collected from the following references:

CERA (2013). Port Hills community meetings. http://cera.govt.nz/port-hills/community-meetings. Accessed 24 Jan 2013.

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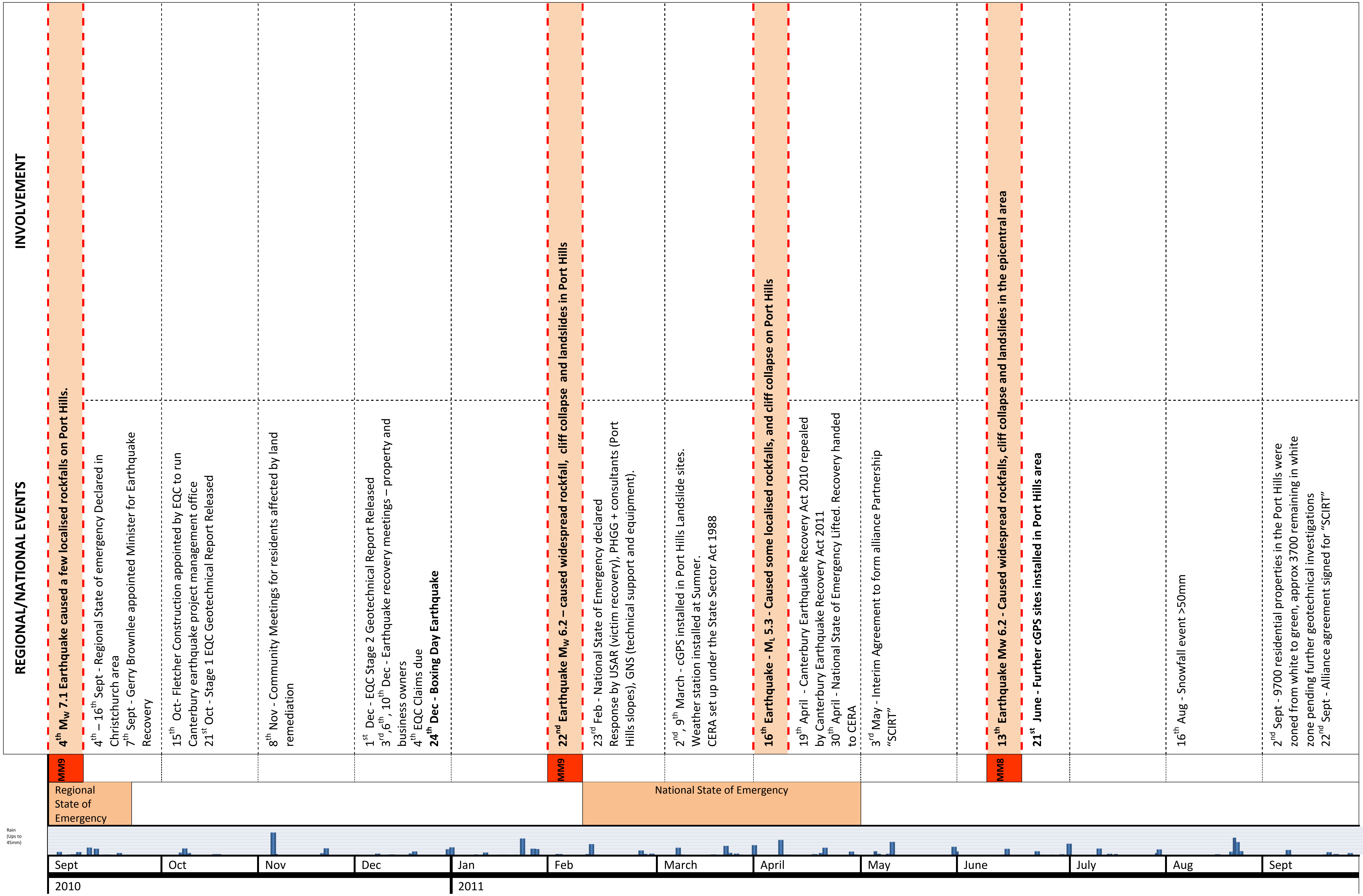
NIWA (2013) Cliflo: The National Climate Database. http://cliflo.niwa.co.nz/. Accessed 4 March 2013.

C1: Sept 2010- Sept 2012 Port Hills Geotechnical Response Timeline



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Participants Name: _____________
Date of Interview: _____________

C1: Sept 2010-Sept 2012 Port Hills Geotechnical Response Timeline

INVOLVEMENT

REGIONAL/NATIONAL EVENTS

1st, 31st Oct - Water level instrument installed in Port Hills to monitor landslide
19th Oct - Rainfall - 50mm rain fell - slips and affects on Port Hills slope stability

1st, 3rd Nov - Water level instrument installed in Port Hills to monitor landslide

19th Dec - 1600 properties in Port Hills rezoned from white to green zone. 11300 homes green, 2100 white

23rd Earthquakes Mw 5.8 ,6.0- Caused some localised rockfalls and cliff collapse on Port Hills

MM7

27th Jan - Ground truthing of GNS reports begins

27th Feb – Community Meeting for White Zone residents

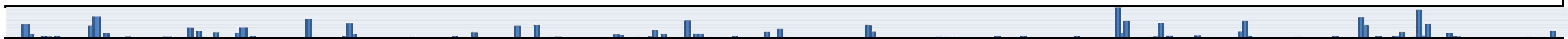
3rd – 9th March - Community Meetings for white zone residents

1st April - Geomorphic mapping of all PHGG sectors completed
1st April - Christchurch Central Development Unit set up within CERA responsible for delivering Central Recovery Plan

18th May - Minister announced 421 properties on the Port Hills now zoned green, leaving 1679 houses still under review

17th Aug - 121 of 163 white zone properties re-zoned red. 5 properties rezoned green, 37 remain white.

13th Sept - 37 properties at risk from rockfall also zoned red. 8 remaining white in landslip zone will become green zone at the end of October 2012
28th Sept - Christchurch City Council releases GNS reports about instability in Port Hills and life-safety risk assessments.



Oct	Nov	Dec	Jan	Feb	March	April	May	June	July	Aug	Sept
2011			2012								

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University of Canterbury

Participants Name: _____________
Date of Interview: _____________

C2: 22nd Feb – 30th April 2011 Port Hills Geotechnical Response Timeline (10 week timeline)

	February 22nd – 28th	March 1st – 7th	8th – 14th	15th – 21st	22nd – 28th	April 29th – 4th	5th – 11th	12th – 18th	19th – 25th	26th – 30th
INVOLVEMENT										
PORT HILLS EVENTS	**22nd Earthquake M_W 6.2 – caused widespread rockfall, cliff collapse and landslides in Port Hills** Landslide response by USAR specialists, PHGG and GNS Science Landslide Recovery Team - Identify types of slope failure from aerial and ground reconnaissance Co-ordination between groups - USAR (victim recovery), PHGG (assigned areas), GNS (technical support and equipment).	CERA set up under the State Sector Act 1988 2nd March - NZ Aerial Mapping undertook an aerial mosaic (approx 10 days after quake) 10 cm pixel ground resolution 2nd cGPS installed in Port Hills Landslide sites	9th March - cGPS installed in Port Hills Landslide sites. Weather station installed at Sumner.					**16th Earthquake - M_L 5.3 - Caused some localised rockfalls, and cliff collapse on Port Hills**	19th April - Canterbury Earthquake Recovery Act 2010 repealed by Canterbury Earthquake Recovery Act 2011	30th April - National State of Emergency Lifted. Recovery handed to CERA
	MM9									
	National State of Emergency									

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University of Canterbury
UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND

Participants Name: ______________
Date of Interview: ______________

C3: 22nd Feb – 7th March 2011 Port Hills Geotechnical Response Timeline (2 week timeline)

INVOLVEMENT

PORT HILLS EVENTS

22nd Feb: **Earthquake M_W 6.2 – caused widespread rockfall, cliff collapse and landslides in Port Hills**

23rd Feb:
National State of Emergency declared
Landslide response by USAR specialists, PHGG and GNS Science
Landslide Recovery Team - Identify types of slope failure from aerial and ground reconnaissance

2nd March:
NZ Aerial Mapping undertook an aerial mosaic (approx 10 days after quake) 10 cm pixel ground resolution

cGPS installed in Port Hills Landslide sites

MM9

National State of Emergency

February							March						
22nd	23rd	24th	25th	26th	27th	28th	1st	2nd	3rd	4th	5th	6th	7th

Dept of Geological Sciences
University of Canterbury

Participants Name: _____________
Date of Interview: _____________


C4: Topographic Map of Port Hills
topomap.co.nz Images sourced from LINZ Topographic Maps. Crown Copyright Reserved.
Sumner
Lyttelton
Diamond Harbour
Lyttelton Harbour / Whakaraupō
Otamahua / Quail Island
Governors Bay
Charteris Bay
Te Wharau / Charteris Bay
Head of the Bay
Purau
Purau Bay
Port Levy
Mt Evans
Awaroa / Godley Head
Adderley Head
Waitata / Little Port Cooper
Te Pohue / Camp Bay
Cass Bay
Rapaki
Taukahara
Heathcote Valley
Mount Pleasant
Redcliffs
Ferrymead
Cashmere
Westmorland
Halswell
Cracroft
Sydenham
Spreydon
Beckenham
Hillsborough
Huntsbury
Opawa
Woolston
Somerfield
Hoon Hay
Scarborough
Taylors Mistake
Evans Pass
Mt Cavendish
Mt Vernon
Sugarloaf
Marleys Hill
Ohinetahi
Allandale
Mansons Peninsula
King Billy Island
Moepuku Point
Ripapa Island
Fort Jervois
Parson Rock
Kamautaurua Island
Te Waipapa / Diamond Harbour
Te Awaparahi
Battery Point
Officers Point
Sticking Point
Coopers Knob
Gibraltar Rock
Teddington
Quail Shelter
Pukerauaruhe Island
Horomaka Island
Puari
Livingstone Bay
Breeze Bay
Mechanics Bay
Sumner Head
Whitewash Head
Shag Rock
Cave Rock
Moncks Bay
Lions Head
Kaitorete
Southshore

Appendix D – University of Canterbury Human Ethics application

Appendix D provides documentation of the low risk University of Canterbury Human Ethics application, and associated amendments to the application conducted throughout the research. The following documents are included:

D1 Low risk human ethics application

D1 Amendment 1 to ethics application and approval

D3 Amendment 2 to ethics application and approval

D4 Amendment 3 to ethics application and approval

D5 Amendment 4 to ethics application and approval

UNIVERSITY OF CANTERBURY

HUMAN ETHICS COMMITTEE

UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND

LOW RISK APPLICATION FORM

(For research proposals which are not considered in full by the University Human Ethics Committee)

FOR STUDENT RESEARCH UP TO AND INCLUDING MASTERS LEVEL

ETHICAL APPROVAL OF LOW RISK RESEARCH INVOLVING HUMAN PARTICIPANTS REVIEWED BY DEPARTMENTS

Please read the important notes appended to this form before completing the sections below

1 **RESEARCHER'S NAME:** Katherine Yates

2 **NAME OF DEPARTMENT OR SCHOOL:** Geological Sciences

3 **EMAIL ADDRESS:** Katherine.yates@pg.canterbury.ac.nz

4 **TITLE OF PROJECT:** Post-disaster Risk Assessment for Hilly Terrain exposed to Seismic Loading

5 **PROJECTED START DATE OF PROJECT:** 21-01-2013

6 **STAFF MEMBER/SUPERVISOR RESPONSIBLE FOR PROJECT:** Dr Marlene Villeneuve (Engineering Geology), Dr Thomas Wilson (Hazard and Disaster Management)

7 **NAMES OF OTHER PARTICIPATING STAFF AND STUDENTS:**

8 **STATUS OF RESEARCH:** Master of Science thesis

9 **BRIEF DESCRIPTION OF THE PROJECT:**
Please give a brief summary (approx. 300 words) of the nature of the proposal in lay language, including the aims/objectives/hypotheses of the project, rationale, participant description, and procedures/methods of the project:

The aim of the project is to analyse and review the approach to geotechnical risk assessments of landslides and rockfall in the Port Hills following the 2010-2011 Christchurch earthquake sequence. The term "geotechnical" addresses the study of the engineering behaviour of geological materials and includes the mechanics of landslides, rockfall and other slope failures.

Due to the unpredictable nature of an earthquake and the potential for geotechnical failures to take place in New Zealand it is important that guidelines for geotechnical risk assessment are developed so that in the event of another large earthquake near a populated area effective risk assessment can be undertaken.

To establish these guidelines a series of interviews will be undertaken with key municipal (council), emergency management, central government, and geotechnical industry stakeholders who were operationally involved with or managed the geotechnical risk assessment that took place post-earthquake. Participants will be selected on the basis of their professional roles and through Dr Villeneuve's and Dr Wilson's professional contacts. Interviews will be voluntary (see Information Sheet and Consent form).

A semi-structured interview approach will be taken. The interview will be guided by a series of prepared questions (attached) with the intention that additional questions may be added by the interviewer to follow up key information as the interview progresses. Additional questions will be influenced by the responses given by the participant. Prepared questions (listed below) have been formed to walk the participant through the response sequence and highlight changes, goals and tasks during that time.

These prepared questions will be tailored to address the specific role of the participant in the response efforts. For example the geotechnical engineer will have a slightly different question set to a participant from a municipal authority who managed the geotechnical risk assessment response. Both question set will however will be based on a similar progression.

Questions for a Geotechnical Engineer

Introduction – Past experience

1. Can you give an overview of your training and previous experience in geotechnical engineering and disaster response?

Christchurch Earthquake

When did you become involved:

2. After which earthquake were you involved in the geotechnical response?
3. How did you become involved in the response?

Where did you work:

4. Where were you mobilised to in the Port Hills and how did this change over time? (Indicate on map)
5. Why were you placed in this/these particular location(s) or area(s)?

What did you do:

6. What was your role in the response following the earthquakes and how did this change over time?
7. What were the key events/decisions that resulted in a change in direction for your work in the response?
8. What was the method you used to assess the risk of slope failures or geotechnical issues and how was this successful/not successful?
9. Do you feel your decisions and analysis of geotechnical features induced by the earthquake were consistent from the time of the event to 12 months later?

Who did you interact with:

10. Who was responsible for co-ordinating the response and making key decisions in your area(s), how did this change over time?
11. Who were the main people you interacted with during the response?
12. Was there a reporting system established between you and your peers in the initial phases of your involvement? How did this change over time?
13. Was it obvious which authorities were responsible for the response in the Port Hills immediately after the earthquake?

Conclusion – Current responsibilities?

14. What is your current role in the response to the earthquake?

Further Reflection

15. Do you have any further reflections on the event?
16. What are the three most important lessons you have learnt from responding to the earthquake sequence?

Questions for personnel involved in management/coordination of the geotechnical risk assessment response on the Port Hills.

Introduction – Past experience

1. Can you give an overview of your previous training and experience in management and disaster response?

Christchurch Earthquake

When did you become involved:

2. After which earthquake were you involved in the earthquake response?
3. How did you become involved in the response?

Where did you work:

4. Did you have a specific area of concern in the Port Hills?
5. Why did this area become the focus of your efforts and how did this progress over time?

What did you do:

6. What was your role in the response following the earthquakes and how did this change over time?
7. What did your role require you to achieve? How did this evolve over time?
8. How did your responsibilities change over time?
9. What were your priorities during the earthquake response? Why were these tasks your priorities?
10. What methods did you use to ensure these priorities were achieved?
11. Did you have a framework in place for managing the geotechnical risk assessment response?
12. Why did you use this management strategy? What were the limitations or benefits of this strategy?

13. Do you feel decisions have been consistent from the time of the event to 12 months later?

Who did you interact with:

14. How did you fit into the structure of the emergency response? How did this change over time?
15. Was it obvious which authorities were responsible for the response in the Port Hills immediately after the earthquake?
16. Was there a reporting system established between you and your peers in the initial phases of your involvement? How did this change over time?

Conclusion – Current responsibilities

17. What is your current role in the response to the earthquake?

Further Reflection

18. Do you have any further reflections on the event?
19. What are the three most important lessons you have learnt from responding to the earthquake sequence?

During the interview, participants will be presented with a timeline outlining major events throughout the earthquake sequence (attached). This timeline will commence from the 4 September 2010 earthquake and include each major aftershock that initiated slope movements. It will include additional secondary information, such as large rainfall events, appointment of major agencies or ministers related to the response, major decisions made by these agencies/people and dates of the declaration of the National State of Emergency etc.

The timeline provides an outline of influential events which may trigger memories of key events or decisions, elicit temporally relevant opinions and give the opportunity for reflection of the event. The use of a timeline is designed to reveal how the role of the participant changed over time, develop an understanding of key outcomes that were required for their role, and what would be useful in the future if this event were repeated (i.e. lessons).

A 1:10,000 topographic map of the Port Hills will also be provided for aid in spatial discussions. A new timeline and map will be unique to each interview, so they may be annotated by the participant and interviewee. Once annotated by the participant the timeline and map will treated as part of the confidential material.

Participants from the Department of Geological Sciences (University of Canterbury), Christchurch City Council, Environment Canterbury, GNS Science, Earthquake Commission, and the Ministry of Civil Defence and Emergency Management will be interviewed throughout late February to April. A selected sub-set of participants will be interviewed again approximately six months following the first interview with the aim to assess any change in the situation in light of current events and further reflection.

Interviews will be undertaken by the lead researcher (Yates).

Interviews will be voluntary and only cover topics relating to the participants professional role.

Each participant will be asked to sign a consent form, which allows information given within the discussion to be used in the research (attached). He/she will also be required to agree to confidentiality of the information.

Participants will be fully informed of the project aims and objectives before agreeing to commence the interview, and will be advised that they are free to cease the interview at any stage or decline to answer any particular question if uncomfortable. The participants will be able to ask the interviewer questions regarding the interview and research project at any time. The participants will have the option to choose the location of the interview.

Once the interview has been completed a series of main points or notes of main points covered in the interview will be sent to the participant for their review, they will be given 5 days upon receiving the documentation to review these.

With the permission of the participant interviews will be recorded on a digital recorder. Records will be held on a password protected external hard drive and backed up on the Geological Sciences Network server which is both password protected and encrypted. Access to these records will be restricted to Katherine

Yates, Marlene Villeneuve, and Thomas Wilson. Records will be kept until the thesis is published and then destroyed. Physical notes, tapes and the external hard drive will be kept in a locked drawer inside a locked office in the Geological Sciences Department in the University of Canterbury.

Information given from the participant will not be used for any other purposes than for this research thesis and possible publication in a peer-reviewed academic journal.

No participant will be identified by name in any of the documents associated with the research project. Contact details of the participants will not be given out to any other individuals or external bodies. Each participant will be given the opportunity to own a copy of the thesis (at completion) or any associated documentation.

10 WHY IS THIS A LOW RISK APPLICATION?
Description should include issues raised in the Low Risk Checklist.
Please give details of any ethical issues which were identified during the consideration of the proposal and the way in which these issues were dealt with or resolved.

To establish these guidelines a series of interviews will be undertaken with key municipal (council), emergency management, central government, and geotechnical industry stakeholders who were operationally involved with or managed the geotechnical risk assessment that took place post-earthquake. Participants will be selected on the basis of their professional roles and through Dr Villeneuve's and Dr Wilson's professional contacts. Interviews will only cover material which participants can reasonably expect to address in their professional roles.

Throughout the earthquake sequence there have been times where the zoning issues of properties in the Port Hills has been a controversial topic. As a result of this many of the participants may find the topic of land zoning issues a sensitive aspect of the geotechnical response to the earthquake sequence. As noted above, participant do not have to answer any question, and if the interviewer notices any signs of distress or discomfort, they will remind the participant of their right to refuse to answer and/or move on with questioning.

Additionally, we would like to note that the intention of the project is not to highlight political or personal failures within the risk assessment process, nor create conflict between public or private entities that participated within the response to the Christchurch earthquake sequence. Any such information given from the participant will not be used within the thesis for protection of the interviewee, researcher and the University. The interviewer will remain neutral throughout the interview to reduce the risk of inducement to the participant and reduce encouragement of conflict between parties involved in the response to the earthquakes.

11 PROVIDE COPIES OF INFORMATION & CONSENT FORMS FOR PARTICIPANTS
These forms should be on University of Canterbury Departmental letterhead. The name of the project, name(s) of researcher(s), contact details of researchers and the supervisor, names of who has access to the data, the length of time the data is to be stored, that participants have the right to withdraw participation and data provided without penalty, and what the data will be used for should all be clearly stated. A statement that the project has been reviewed approved by the appropriate department and the University of Canterbury Human Ethics Committee Low Risk Approval process should also be included.

Please ensure that Section A, B and C below are all completed

APPLICANT'S SIGNATURE: .... Date ....

A SUPERVISOR DECLARATION:

1 I have made the applicant fully aware of the need for and the requirement of seeking HEC approval for research involving human participants.
2 I have ensured the applicant is conversant with the procedures involved in making such an application.
3 In addition to this form the applicant has individually filled in the full application form which has been reviewed by me.

SIGNED (Supervisor): .... Date 15/2/13

B SUPPORTED BY THE DEPARTMENTAL/SCHOOL RESEARCH COMMITTEE:

Name Tim Davies

Signature: .... Date 8/2/13

C APPROVED BY HEAD OF DEPARTMENT/SCHOOL:

Name ....

Signature: J. Pettinga Date 15/2/13

SUBMISSION OF APPLICATION:
- Please attach copies of any Information Sheet and Consent Form.
- Forward two hard copies to: The Secretary, Human Ethics Committee, Okeover House.

NOTES ON PROCEDURE:
- The Chair of the University of Canterbury Human Ethics Committee will review this application.
- In normal circumstances queries will be forwarded via email to the applicant within 7 days.
- Please include a copy of this form as an appendix in your thesis or course work.

ACTION TAKEN BY HUMAN ETHICS COMMITTEE:

☐ Added to Low Risk Reporting Database

☐ Referred to University of Canterbury HEC

☐ Referred to another Ethics Committee - please specify:

....

Reviewed by: .... Date ....

NOTES CONCERNING LOW RISK REPORTING SHEETS

1. This form should only be used for proposals which are Low Risk as defined in the University of Canterbury Human Ethics Committee Principles and Guidelines policy document, and which may therefore be properly considered and approved at departmental level under Section 5 of that document.

2. Low Risk applications are:

   a Masters theses where the projects do not raise any issue of deception, threat, invasion of privacy, mental, physical or cultural risk or stress, and do not involve gathering personal information of a sensitive nature about or from individuals.

   b Masters level supervised projects undertaken as part of specific course requirements where the projects do not raise any issue of deception, threat, invasion of privacy, mental, physical or cultural risk or stress, and do not involve gathering personal information of sensitive nature about or from individuals.

   c Undergraduate and Honours class research projects which do not raise any issue of deception, threat, invasion of privacy, mental, physical or cultural risk or stress, and do not involve gathering personal information of sensitive nature about or from individuals, but do not have blanket approval as specified in Section 4 of the Principles and Guidelines.

3. No research can be counted as low risk if it involves:

   (i) invasive physical procedures or potential for physical harm
   (ii) procedures which might cause mental/emotional stress or distress, moral or cultural offence
   (iii) personal or sensitive issues
   (iv) vulnerable groups
   (v) Tangata Whenua
   (vi) cross cultural research
   (vii) investigation of illegal behaviour(s)
   (viii) invasion of privacy
   (ix) collection of information that might be disadvantageous to the participant
   (x) use of information already collected that is not in the public arena which might be disadvantageous to the participant
   (xi) use of information already collected which was collected under agreement of confidentiality
   (xii) participants who are unable to give informed consent
   (xiii) conflict of interest e.g. the researcher is also the lecturer, teacher, treatment-provider, colleague or employer of the research participants, or there is any other power relationship between the researcher and the research participants.
   (xiv) deception
   (xv) audio or visual recording without consent
   (xvi) withholding benefits from “control” groups
   (xvii) inducements
   (xviii) risks to the researcher

   This list is not definitive but is intended to sensitise the researcher to the types of issues to be considered. Low risk research would involve the same risk as might be encountered in normal daily life.

4. Responsibility

   Supervisors are responsible for:

   (i) Theses where the projects do not raise any issues listed below.
   (ii) Masters level supervised projects undertaken as part of specific course requirements where the projects do not raise any issue.
   (iii) Undergraduate and Honours class research projects which do not raise any issue listed but do not have blanket approval as specified in the Principles and Guidelines.

Heads of Department are responsible for:

(i) Giving final departmental approval for the low risk application.
(ii) Ensuring a copy of all applications are kept on file in the Department/School.

5. A separate low risk form should be completed for each teaching or research proposal which involves human participants and for which ethical approval has been considered or given at Departmental level.

6. The completed and signed Application form together with copies of any Information Sheet or Consent Form should be submitted to the Secretary, Human Ethics Committee, Okeover, as soon as the proposal has been considered at departmental level.

7. The Information Sheet and Consent Form should include the statement "This proposal has been reviewed and approved by the Department of ....., University of Canterbury and the University of Canterbury Human Ethics Committee Low Risk process."

8. Please ensure the Consent Form and the Information Sheet have been carefully proof-read; the institution as a whole is likely to be judged by them.

9. The research must be consistent with the University of Canterbury Human Ethics Committee Principles and Guidelines. Refer to the appendices of the UC HEC Principles and Guidelines for guidance on information sheets and consent forms.

10. Please note that if the nature, procedures, location or personnel of the research project changes after departmental approval has been given in such a way that the research no longer meets the conditions laid out in Section 5 of the Principles and Guidelines, a full application to the Human Ethics Committee must be submitted.

11. This form is available electronically at: http://www.canterbury.ac.nz/humanethics

CHECKLIST

Please check that your application/summary has discussed:

- Procedures for voluntary, informed consent
- Privacy & confidentiality
- Risk to participants
- Obligations under the Treaty of Waitangi
- Needs of dependent persons
- Conflict of interest
- Permission for access to participants from other individuals or bodies
- Inducements

In some circumstances research which appears to meet low risk criteria may need to be reviewed by the University of Canterbury Human Ethics Committee. This might be because of requirements of:

- The publisher of the research.
- An organisation which is providing funding resources, existing data, access to participants etc.
- Research which meets the criteria for review by a Health and Disability Ethics Committee – see HRC web site.

If you require advice on the appropriateness of research for low risk review, please contact the Chair of the University of Canterbury Human Ethics Committee.

Dept of Geological Sciences
University of Canterbury
+64 3 364 2987

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Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Information Sheet for Interview Participants

Thank you for agreeing to participate in this study. Please read the information sheet and the attached the consent form in detail before signing either of the documents.

This information sheet outlines the purpose, benefits, and methods of the research, and explains your rights a participant in this study. If at any stage you wish to enquire about this research, feel free to contact any of the research contributors listed below. This research project has been funded by Environment Canterbury.

Contacts

Katherine Yates
University of Canterbury
katherine.yates@pg.canterbury.ac.nz

Supervisors

Dr Marlene Villeneuve
University of Canterbury
Marlene.Villeneuve@canterbury.ac.nz
+64 3 364 2987 ext. 45682

Dr Thomas Wilson
University of Canterbury
Thomas.wilson@canterbury.ac.nz
+64 3 364-2987 ext 45511

Project Background

The purpose of this study:

- To gather information about your experiences and involvement in the geotechnical response to the Christchurch earthquake sequence.
- Use the information provided by you and other participants to develop a framework for emergency response to earthquake induced geotechnical failures

Benefits of this research:

- Develop guidelines for geotechnical response to earthquakes in hilly terrain.
- Preparedness for future earthquake events and associated geotechnical hazards that may occur in New Zealand.

Methods of this research:

- In this phase of the research, one-on-one interviews will take place with key municipal, management and operational stakeholders who were involved in the geotechnical risk assessment during the Christchurch earthquake sequence.
- Information from this research will be used to reflect on the response to geotechnical hazards induced by the Christchurch earthquake sequence and identify useful response strategies for the future.

Interview Participation:

Participation in this interview is voluntary. If you feel uncomfortable at any stage in the interview and feel you no longer want to participate in the study, you have the right to withdraw from the study at any time. If you do choose to withdraw, any data from the interview will not be used in the research project and will be destroyed. If you have any questions or concerns regarding the study, please don't hesitate to ask.

Interviews will one-on-one and will be recorded with an audio device and later processed into written dialogue.

Data Storage:

The audio records will be kept confidential on a password secured external hard drive. The external hard drive and written notes from the interview will be stored in a locked drawer in a locked office in the Geological Sciences Department of Canterbury University. Audio records of interviews will be destroyed when the thesis is published. Access to the data will be restricted to me (Katherine Yates), and my supervisors (Dr Marlene Villeneuve and Dr Thomas Wilson).

Data use:

Information gathered from this interview will be used as data in the research efforts towards a Master's thesis and possible publication in a peer-reviewed academic journal. Please be aware your name and personal details will be kept anonymous, however with your permission direct quotes may be used.

Once the interview has finished, notes from the interview will be written up and sent to you for review. Upon receiving this you will given 5 days to revise the information you have given before the information will be used for the research.

Additionally, please be aware that the intention of this project is not to highlight political, organisational or personal failures that may have occurred throughout the earthquake response phase, nor create conflict between parties. Rather, the goal is to extract the lessons learnt during this event for application in future New Zealand disasters. Therefore, if there is a risk of this occurring, any such information given from the participant will not be used in the thesis or associated publications.

Documents published throughout the study or at the conclusion of the study will be accessible to the participant.

Please read the attached consent form and sign to confirm participation.

Please feel free to keep this information sheet.

Thank you for participating in this study.

Dept of Geological Sciences
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UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Consent for participation in Interview Research

Contacts

Katherine Yates
University of Canterbury
katherine.yates@pg.canterbury.ac.nz

Supervisors
Dr Marlene Villeneuve
University of Canterbury
Marlene.Villeneuve@canterbury.ac.nz
+64 3 364 2987 ext. 45682

Dr Thomas Wilson
University of Canterbury
Thomas.wilson@canterbury.ac.nz
+64 3 364-2987 ext 45511

1. I understand that my participation in this interview is voluntary and I have the right to withdraw from the interview or decline to answer a question at anytime.
2. Participation will involve being interviewed one-on-one by Katherine Yates (MSc Candidate) from the University of Canterbury. I understand the interview will be recorded using audio equipment and written notes. A written dialogue will be produced following the interview. If I do not wish to be recorded then I understand I cannot participate any further in the study.
3. I acknowledge that this research project is funded by Environment Canterbury.
4. I understand that to protect my privacy, information, records and data from the interview will be kept confidential. Information I provide will be used anonymously in the thesis publication and associated document, however I permit direct quotes to be used.
5. I understand that electronic data collected from my interview will be stored on a password secured external hard drive. The external hard drive and written notes from the interview will be stored in a locked drawer in a locked office. Data will be stored until the thesis is published. Access to the data will be limited to Katherine Yates, Dr Marlene Villeneuve and Dr Thomas Wilson (Geological Sciences, University of Canterbury).
6. I understand that the information gathered from this interview will be used in Katherine Yates' Master of Science thesis and possibly published in a peer-reviewed academic journal.

7. I understand that I will be sent a document after the interview outlining the main points from the interview. I understand I will have 7 days to review this documentation before the information will be used in the research.
8. I am aware that the intention of this project is not to highlight political, organisational or personal failures that may have occurred throughout the earthquake response phase, nor create conflict between parties. Any conflicting information given in this way will not be used in the thesis.
9. I acknowledge that this proposal has been reviewed and approved by the Department of Geological Science, University of Canterbury and the University of Canterbury Human Ethics Committee Low Risk process.
10. I have read, understood and agreed with both the information form and consent form provided to me. All my questions regarding the study have been answered satisfactorily.
11. A copy of this consent form and the information sheet has been given to me.

Name:	*Name:* Katherine Yates
Date:	*Date:*
Signed: ______________________	*Signed:* ______________________

2010-2012 Port Hills Geotechnical Response Timeline

Participants Name: ________

Date of Interview: ________

Year	Month	State of Emergency	MM	PORT HILLS EVENTS	REGIONAL/NATIONAL EVENTS
2010	Sept	Regional State of Emergency	MM9	**4th M_W 7.1 Earthquake caused a few localised rockfalls and cliff collapse on Port Hills.**	
				Rockfall: Castle Rock, Summit Rd, (Gondola), Dyers Pass Rd and Sumner Road. Road Closures at each. 11th, 13th Clearing & blasting rock at Sumner Road	4th Regional State of emergency Declared in Christchurch area 7th Gerry Brownlee appointed Minister for Earthquake Recovery 14th Canterbury Earthquake Response and Recovery Act 2010 16th Regional State of Emergency Lifted.
	Oct				15th Fletcher Construction appointed by EQC to run Canterbury earthquake project management office 21st Stage 1 of Geotechnical Report Released
	Nov				8th Community Meetings for residents affected by land remediation
	Dec				1st EQC Stage 2 Geotechnical Report Released 3rd, 6th, 10th Earthquake recovery meetings – property and business owners 4th EQC Claims due **24th Boxing Day Earthquake**
2011	Jan				
	Feb	National State of Emergency	MM9	**22nd Earthquake M_W 6.2 – caused widespread rockfall, cliff collapse and landslides in Port Hills**	
				30th Co-ordination between groups - USAR (victim recovery), PHGG (assigned areas), GNS (technical support and equipment).	23rd National State of Emergency declared
	March			2nd, 9th cGPS installed in Port Hills Landslide sites. Weather station installed at Sumner.	CERA set up under the State Sector Act 1988
	April			**16th Earthquake - M_L 5.3 - Caused some localised rockfalls, and cliff collapse on Port Hills**	
					19th Canterbury Earthquake Recovery Act 2010 repealed by Canterbury Earthquake Recovery Act 2011 30th National State of Emergency Lifted. Recovery handed to CERA
	May				3rd Interim Agreement to form alliance Partnership "SCIRT"
	June			Doubled Barriers along Wakefield Ave and Peacocks	
			MM8	**13th Earthquake Mw 6.2 - Caused widespread rockfalls, cliff collapse and landslides in the epicentral area**	
				21st Further cGPS sites installed in Port Hills area	
	July				
	Aug				16th Snowfall event >50mm
	Sept			2nd 9700 residential properties in the Port Hills were zoned from white to green, approx 3700 remaining in white zone pending further geotechnical investigations 7-10th Community Meetings by Jan Cupec and team - Update on Geotechnical Work in Port Hills	22nd Alliance agreement signed for "SCIRT"

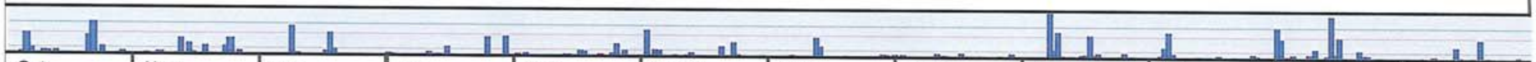
Dept of Geological Sciences
University of Canterbury

UC UNIVERSITY OF CANTERBURY

2010-2012 Port Hills Geotechnical Response Timeline

Month	PORT HILLS EVENTS	REGIONAL/NATIONAL EVENTS
Oct 2011	1st, 31st Water level instrument installed in Port Hills to monitor landslide 19th Rainfall - 50mm rain fell - slips and affects on Port Hills slope stability	
Nov	1st, 3rd Water level instrument installed in Port Hills to monitor landslide	
Dec	19th 1600 properties in Port Hills rezoned from white to green zone: 11300 homes green, 2100 white	
Dec (MM7)	23rd Earthquakes Mw 5.8, 6.0- Caused some localised rockfalls and cliff collapse on Port Hills	
Jan 2012	27th Ground truthing GNS reports begins	
Feb	27th – Community Meeting for White Zone residents	
March	3rd – 9th Community Meetings for white zone residents	
April	1st Geomorphic mapping of all PHGG sectors completed	1st Christchurch Central Development Unit set up within CERA responsible for delivering Central Recovery Plan
May	18th Minister announced 421 properties on the Port Hills now zoned green, leaving 1679 houses still under review	
June		
July		
Aug	17th 121 of 163 white zone properties re-zoned red. 5 properties rezoned green, 37 remain white.	
Sept	13th 37 properties at risk from rockfall also zoned red. 8 remaining white in landslip zone will become green zone at the end of October 2012 28th Christchurch City Council releases GNS reports about instability in Port Hills and life-safety risk assessments.	

Rain (Ups to 45mm)



Oct | Nov | Dec | Jan | Feb | March | April | May | June | July | Aug | Sept

2011 | 2012

Dept of Geological Sciences
University of Canterbury

Participants Name: ____________

Date of Interview: ____________

Legend for text colours	
(blue)	Local/National Political Decision
(dark grey)	Geotechnical Event/Management Decision
(orange)	Community Meeting
(green)	Natural Event (i.e. Rainfall)

Dept of Geological Sciences
University of Canterbury

Participants Name: ____________
Date of Interview: ____________

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2013/05/LR

8 March 2013

Katherine Yates
Department of Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Katherine

Thank you for forwarding your Human Ethics Committee Low Risk application for your research proposal "Post-disaster assessment for hilly terrain exposed to seismic loading".

I am pleased to advise that this application has been reviewed and I confirm support of the Department's approval for this project.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 4 March 2013.

With best wishes for your project.

Yours sincerely

L MacDonald

Lindsey MacDonald
Chair, Human Ethics Committee

D2 Ethics application amendment 1

Amendment to application HEC 2013/05/LR.

Katherine Yates

To: Human Ethics

Cc: Thomas Wilson

Attachments: Confidentialty agreement.pdf (211 KB)

Tuesday, 26 March 2013 4:50 p.m.

- You forwarded this message on 27/03/2013 5:27 p.m..

Hi Lynda

I would like to make an amendment to the ethics application Ref: HEC 2013/05/LR.

As part of the research process we would now like to engage a transcriber to convert the audio interview dialogue to text.

We have come up with the following conditions for the transcriber to abide by:

- The transcriber will be required to keep audio and text files secure and password protected where possible.
- The transcriber will be required to keep information from the interviews confidential (i.e will not discuss information from the interviews).
- The transcriber will not be made aware of the identity of the participants.
- The transcriber will be required to dispose of both the transcribed dialogue and the audio data once the files have been passed on to the researcher (myself).

The confidentiality agreement has been developed in accordance with these requirements. The transcriber will be required to agree to the conditions and sign the document before receiving the audio data. Two copies of the document will be signed, one for the reference of the researcher, and one to be kept by the transcriber.

A pdf copy of the document is attached.

Please advise of any additional requirements that may be needed for this amendment to be approved.

Kind Regards
Katherine Yates

Dept of Geological Sciences
University of Canterbury
+64 3 364 2987

Post-Disaster Risk Assessment for Hilly Terrain exposed to Seismic Loading.

Transcribers Confidentiality Agreement

This research is being undertaken by Katherine Yates in the Department of Geological Sciences, University of Canterbury. The purpose of the research is to gather information about the experiences and involvement in the geotechnical experts in the response to the Christchurch earthquake sequence. This information will be used to develop guidelines for geotechnical response to earthquakes in hilly terrain and work towards preparedness for future earthquake events and associated geotechnical hazards that may occur in New Zealand.

As a transcriber of this research, I understand that I will be hearing recordings of confidential interviews. The information on these recordings has been revealed by interviewees who agreed to participate in this research on the condition that their interviews would remain strictly confidential. I understand that I have a responsibility to honour this confidentially agreement.

I agree not to share any information on these recordings, about any party, with anyone except the Researcher of this project. Any violation of this and the terms detailed below would constitute a serious breach of ethical standards and I confirm that I will adhere to the agreement in full.

I, ____ agree to:

1. Keep all the research information shared with me confidential by not discussing or sharing the content of the interviews in any form or format (e.g. WAV files, CDs, transcripts) with anyone other than the Researcher.
2. Keep all research information in any form or format (e.g. WAV files, CDs, transcripts) secure while it is in my possession. All transcription files will be password protected where possible.
3. Return all research information in any form or format (e.g. WAV files, CDs, transcripts) to the Researcher when I have completed the transcription tasks.
4. After consulting with the Researcher, erase or destroy all research information in any form or format regarding this research project that is not returnable to the Researcher (e.g. CDs, information stored on my computer hard drive).

Transcriber:

____________________ ____________________ ____________________
(print name) (signature) (date)

Researcher:

____________________ ____________________ ____________________
(print name) (signature) (date)

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch; email: human-ethics@canterbury.ac.nz

1

UNIVERSITY OF CANTERBURY

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2013/05/LR

27 March 2013

Katherine Yates
Department of Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Katherine

Thank you for your request for an amendment to your research proposal "Post-disaster assessment for hilly terrain exposed to seismic loading" as outlined in your email dated 26 March 2013.

I am pleased to advise that this request has been considered and approved by the Human Ethics Committee.

Yours sincerely

Lindsey MacDonald
Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

E S

D3 Ethics application amendment 2

Amendment to application HEC 2013/05/LR

Katherine Yates

To: Human Ethics

Cc: Thomas Wilson; Marlene Villeneuve

Attachments: 13-6-2013 TIMELINE TO BE S~1.pdf (645 KB)

Thursday, 13 June 2013 9:23 a.m.

Hi Lynda

I would like to make an amendment to the ethics application Ref: HEC 2013/05/LR.

Prior to interviewing participants we would like to send out the attached timeline for participants to catalogue their involvement in the response to the Christchurch earthquake sequence using the provided dates.

Previously in our application our chosen methodology was to refer to the attached timeline during the interview in order prompt memories of the event sequence. However, we feel that there would be considerable benefit in requesting participants to examine the timeline before the interview and attempt to record their involvement.

Participants will be issued two timelines, one that extends from September 2010 to September 2012, the other from 22nd February 2011 to 7th March 2011. The aim of this is to allow participants to review their involvement after the 22nd February 2011 earthquake in slightly more detail. Both timelines are included in the attached pdf.

Instructions for the participants to fill out the timeline will be listed in email format during communications prior to the interview.

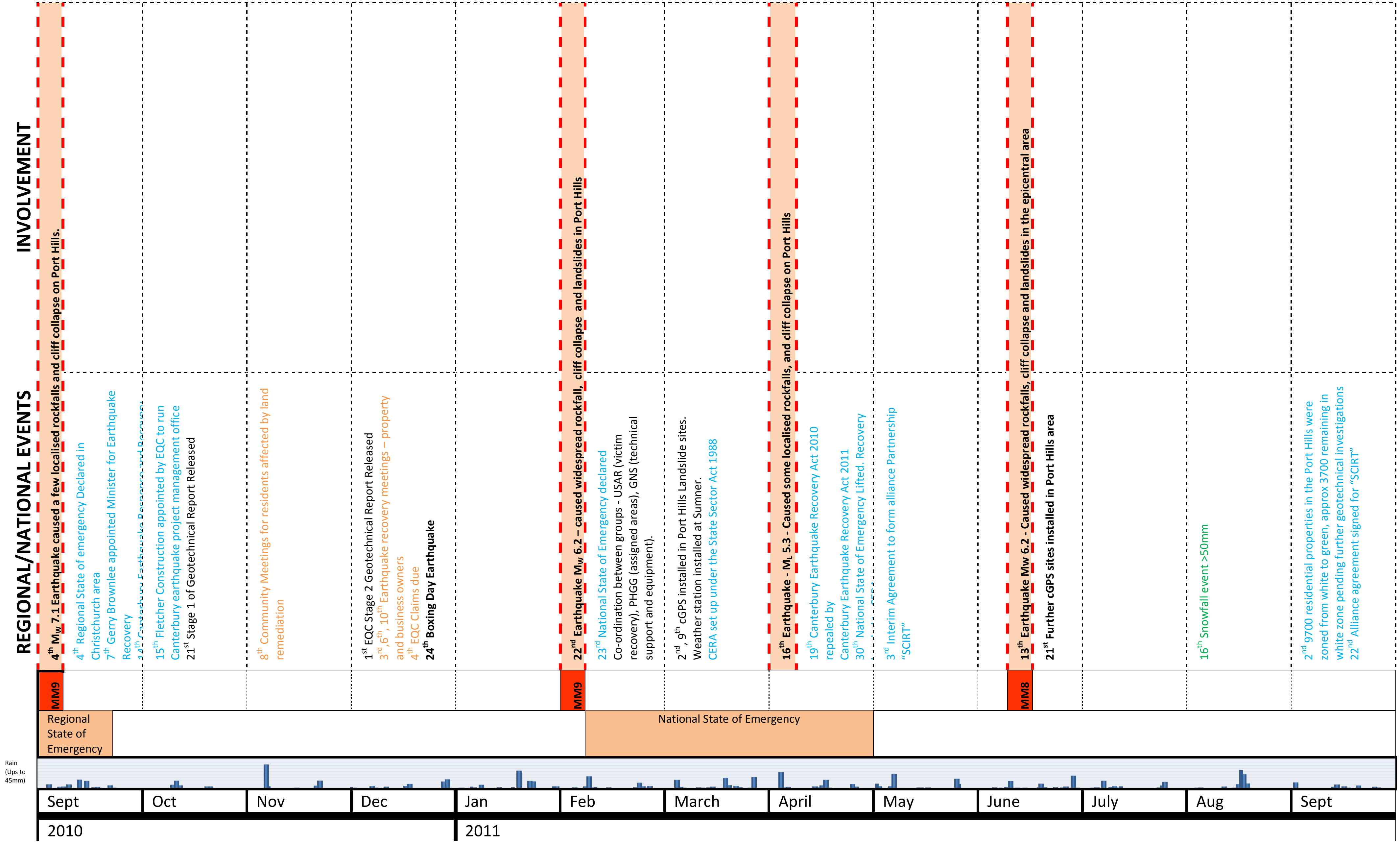
Participants will be requested to keep the timeline confidential and will be required to bring the document to the interview.

After the interview I will retain the participant's timeline and keep it as part of my confidential documentation.

Please advise of any additional requirements that may be needed for this amendment to be approved.

Kind Regards
Katherine Yates

2010-2012 Port Hills Geotechnical Response Timeline



Dept of Geological Sciences
University of Canterbury

Participants Name: ______________

Date of Interview: ______________

2010-2012 Port Hills Geotechnical Response Timeline

Legend for text colours

Blue	Local/National Political Decision
Black	Geotechnical Event/Management Decision
Orange	Community Meeting
Green	Natural Event (i.e. Rainfall)

INVOLVEMENT

REGIONAL/NATIONAL EVENTS

2011

Oct
- 1st, 31st Water level instrument installed in Port Hills to monitor landslide
- 19th Rainfall - 50mm rain fell - slips and affects on Port Hills slope stability

Nov
- 1st, 3rd Water level instrument installed in Port Hills to monitor landslide

Dec
- 19th 1600 properties in Port Hills rezoned from white to green zone. 11300 homes green, 2100 white
- **23rd Earthquakes Mw 5.8 ,6.0- Caused some localised rockfalls and cliff collapse on Port Hills**
- MM7

2012

Jan
- 27th Ground truthing GNS reports begins

Feb
- 27th – Community Meeting for White Zone residents

March
- 3rd – 9th Community Meetings for white zone residents

April
- 1st Geomorphic mapping of all PHGG sectors completed
- 1st Christchurch Central Development Unit set up within CERA responsible for delivering Central Recovery Plan

May
- 18th Minister announced 421 properties on the Port Hills now zoned green, leaving 1679 houses still under review

June

July

Aug
- 17th 121 of 163 white zone properties re-zoned red. 5 properties rezoned green, 37 remain white.

Sept
- 13th 37 properties at risk from rockfall also zoned red. 8 remaining white in landslip zone will become green zone at the end of October 2012
- 28th Christchurch City Council releases GNS reports about instability in Port Hills and life-safety risk assessments.

Rain (Ups to 45mm)

Oct | Nov | Dec | Jan | Feb | March | April | May | June | July | Aug | Sept

2011 | 2012

Dept of Geological Sciences
University of Canterbury
UNIVERSITY OF CANTERBURY

Participants Name: ______________
Date of Interview: ______________

2010-2012 Port Hills Geotechnical Response Timeline

	February 22nd – 28th	March 1st – 7th	8th – 14th	15th – 21st	22nd – 28th	April 29th – 4th	5th – 11th	12th – 18th	19th – 25th	26th – 30th
INVOLVEMENT										
PORT HILLS EVENTS	**22nd Earthquake M_W 6.2 – caused widespread rockfall, cliff collapse and landslides in Port Hills** Landslide response by USAR specialists, PHGG and GNS Science Landslide Recovery Team - Identify types of slope failure from aerial and ground reconnaissance Co-ordination between groups - USAR (victim recovery), PHGG (assigned areas), GNS (technical support and equipment).	CERA set up under the State Sector Act 1988 2nd NZ Aerial Mapping undertook an aerial mosaic (approx 10 days after quake) 10 cm pixel ground resolution 2nd cGPS installed in Port Hills Landslide sites	9th cGPS installed in Port Hills Landslide sites. Weather station installed at Sumner.					**16th Earthquake - M_L 5.3 - Caused some localised rockfalls, and cliff collapse on Port Hills**	19th Canterbury Earthquake Recovery Act 2010 repealed by Canterbury Earthquake Recovery Act 2011	30th National State of Emergency Lifted. Recovery handed to CERA
	MM9									
	National State of Emergency									

Dept of Geological Sciences
University of Canterbury
UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND

Participants Name: ______________

Date of Interview: ______________

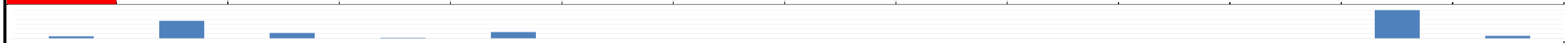
2010-2012 Port Hills Geotechnical Response Timeline

INVOLVEMENT

PORT HILLS EVENTS

Date	Port Hills Events
February 22nd	**Earthquake M_W 6.2 – caused widespread rockfall, cliff collapse and landslides in Port Hills** (MM9)
February 23rd	National State of Emergency declared Landslide response by USAR specialists, PHGG and GNS Science Landslide Recovery Team - Identify types of slope failure from aerial and ground reconnaissance
February 24th	
February 25th	
February 26th	
February 27th	
February 28th	
March 1st	
March 2nd	NZ Aerial Mapping undertook an aerial mosaic (approx 10 days after quake) 10 cm pixel ground resolution cGPS installed in Port Hills Landslide sites
March 3rd	
March 4th	
March 5th	
March 6th	
March 7th	

Rain (Ups to 14mm)



Dept of Geological Sciences
University of Canterbury
UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND

Participants Name: ______________
Date of Interview: ______________

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2013/05/LR

14 June 2013

Katherine Yates
Department of Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Katherine

Thank you for your request for an amendment to your research proposal "Post-disaster assessment for hilly terrain exposed to seismic loading" as outlined in your email dated 13 June 2013.

I am pleased to advise that this request has been considered and approved by the Human Ethics Committee.

Yours sincerely

Lindsey MacDonald
Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

E S

D4 Ethics application amendment 3

Amendment to application HEC 2013/05/LR

Katherine Yates

To: Human Ethics

Cc: Thomas Wilson; Marlene Villeneuve

Attachments: (2) Download all attachments
Consent Form 19-06-2013.pdf (259 KB); Information Sheet 19-06-2013.pdf (285 KB)

Wednesday, 19 June 2013 3:02 p.m.

Hi Lynda,

I would like to request an amendment to the ethics application Ref: HEC 2013/05/LR.

I would like to amend my information sheet and consent forms to specifically detail that email correspondence between myself and participants will be kept confidential.

I have amended both documents and attached them to this email - words added to the document are highlighted in yellow so you can find them easily.

I am requesting this amendment because one of my interview participants cannot be interviewed in person, so I intend on sending my question set to them via email. They will also respond to these questions via email. Because of this, I would like to detail that email correspondence will be kept confidential.

Please advise of any additional requirements that may be needed for this amendment to be approved.

Hopefully this will be the last amendment request for a while!

Many thanks
Katherine Yates

Dept of Geological Sciences
University of Canterbury
+64 3 364 2987

Post-Disaster Risk Assessment for Hilly Terrain exposed to Seismic Loading.

Consent for participation in Interview Research

Contacts

Researcher
Katherine Yates
University of Canterbury
katherine.yates@pg.canterbury.ac.nz

Supervisors

Dr Marlene Villeneuve
University of Canterbury
Marlene.Villeneuve@canterbury.ac.nz
+64 3 364 2987 ext. 45682

Dr Thomas Wilson
University of Canterbury
Thomas.wilson@canterbury.ac.nz
+64 3 364-2987 ext 45511

1. I understand that my participation in this interview is voluntary and I have the right to withdraw from the interview or decline to answer a question at anytime.
2. Participation will involve being interviewed one-on-one by Katherine Yates (Researcher) from the University of Canterbury. I understand the interview will be recorded using audio equipment and written notes. A written dialogue will be produced following the interview. If I do not wish to be recorded then I understand I cannot participate any further in the study.
3. I acknowledge that this research project is funded by Environment Canterbury.
4. I understand that to protect my privacy, my email correspondence with the researcher, and information, records or data from the interview will be kept confidential. Information I provide will be kept confidential in the thesis publication and associated documents, however I permit direct quotes to be used.
5. I understand that electronic data collected from my interview will be stored on a password secured external hard drive. The external hard drive and written notes from the interview will be stored in a locked drawer in a locked office. Data will be stored until the thesis is published. Access to the data will be limited to

Katherine Yates, Dr Marlene Villeneuve and Dr Thomas Wilson (Geological Sciences, University of Canterbury).

6. I understand that the information gathered from this interview will be used in Katherine Yates' Master of Science thesis and possibly published in a peer-reviewed academic journal.
7. I understand that I will be sent a document after the interview outlining the main points from the interview. I understand I will have 7 days to review this documentation before the information will be used in the research.
8. I am aware that the intention of this project is not to highlight political, organisational or personal failures that may have occurred throughout the earthquake response phase, nor create conflict between parties. Any conflicting information given in this way will not be used in the thesis.
9. I acknowledge that this proposal has been reviewed and approved by the Department of Geological Science, University of Canterbury and the University of Canterbury Human Ethics Committee Low Risk process.
10. I have read, understood and agreed with both the information form and consent form provided to me. All my questions regarding the study have been answered satisfactorily.
11. A copy of this consent form and the information sheet has been given to me.

Name:	*Name:* Katherine Yates
Date:	*Date:*
Signed: ______________________	*Signed:* ______________________

2

Dept of Geological Sciences
University of Canterbury
+64 3 364 2987

UNIVERSITY OF CANTERBURY

Post-Disaster Risk Assessment for Hilly Terrain exposed to Seismic Loading.

Information Sheet for Interview Participants

Thank you for agreeing to participate in this study. Please read the information sheet and the attached the consent form in detail before signing either of the documents.

This information sheet outlines the purpose, benefits, and methods of the research, and explains your rights a participant in this study. If at any stage you wish to enquire about this research, feel free to contact any of the research contributors listed below. This research project has been funded by Environment Canterbury.

Contacts

Researcher

Katherine Yates
University of Canterbury
katherine.yates@pg.canterbury.ac.nz

Supervisors

Marlene Villeneuve
University of Canterbury
Marlene.Villeneuve@canterbury.ac.nz
+64 3 364 2987 ext. 45682

Thomas Wilson
University of Canterbury
Thomas.wilson@canterbury.ac.nz
+64 3 364-2987 ext 45511

Project Background

The purpose of this study:

- To gather information about your experiences and involvement in the geotechnical response to the Christchurch earthquake sequence.
- Use the information provided by you and other participants to develop a framework for emergency response to earthquake induced geotechnical failures

Benefits of this research:

- Develop guidelines for geotechnical response to earthquakes in hilly terrain.
- Preparedness for future earthquake events and associated geotechnical hazards that may occur in New Zealand.

Methods of this research:

- In this phase of the research, one-on-one interviews will take place with key municipal, management and operational stakeholders who were involved in the geotechnical risk assessment during the Christchurch earthquake sequence.
- Information from this research will be used to reflect on the response to geotechnical hazards induced by the Christchurch earthquake sequence and identify useful response strategies for the future.

Interview Participation:

Participation in this interview is voluntary. Interviews will be one-on-one and recorded with an audio device and later processed into written dialogue.

If you feel uncomfortable at any stage in the interview and feel you no longer want to participate in the study, you have the right to withdraw from the study at time during the interview. If you do choose to withdraw during the interview, any data collected from the interview will not be used in the research project and will be destroyed.

It will not be possible to withdraw from the study once the interview data is incorporated into the larger analysis.

If you have any questions or concerns regarding the study, please don't hesitate to ask.

Data Storage:

The audio records and email correspondence between the participant and the researcher will be kept confidential on a password secured external hard drive. The external hard drive and written notes from the interview will be stored in a locked drawer in a locked office in the Geological Sciences Department of Canterbury University. Audio records of interviews will be destroyed when the thesis is published. Access to the data will be restricted to me (Katherine Yates), and my supervisors (Dr Marlene Villeneuve and Dr Thomas Wilson).

Data use:

Information gathered from this interview will be used as data in the research efforts towards a Master's thesis and possible publication in a peer-reviewed academic journal. Please be aware your name and personal details will be kept confidential, however with your permission direct quotes may be used.

Once the interview has finished, notes from the interview will be written up and sent to you for review. Upon receiving this you will given 5 days to revise the information you have given before the information will be used for the research.

Additionally, please be aware that the intention of this project is not to highlight political, organisational or personal failures that may have occurred throughout the earthquake response phase, nor create conflict between parties. Rather, the goal is to extract the lessons learnt during this event for application in future New Zealand disasters.

Documents published throughout the study or at the conclusion of the study will be accessible to the participant.

The methods for this research has been reviewed and approved by the Department of Geological Science, University of Canterbury and the University of Canterbury Human Ethics Committee Low Risk process.

Please read the attached consent form and sign to confirm participation.

Please feel free to keep this information sheet.

Thank you for participating in this study.

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2013/05/LR – Amendment 3

28 June 2013

Katherine Yates
Department of Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Katherine

Thank you for your request for an amendment to your research proposal "Post-disaster assessment for hilly terrain exposed to seismic loading" as outlined in your email dated 19 June 2013.

I am pleased to advise that this request has been considered and approved by the Human Ethics Committee.

Yours sincerely

Lindsey MacDonald
Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

E S

D5 Ethics application amendment 4

Amendment to application HEC 2013/05/LR

Katherine Yates

To: Human Ethics
Cc: Thomas Wilson; Marlene Villeneuve
Attachments: confidentiality agreement ~1.pdf (51 KB)

Friday, 19 July 2013 1:57 p.m.

Hi Lynda,

Thanks for your quick feedback - I really appreciate it. I have received the required document. The amendment to my ethics application is as follows:

I would like to request an amendment to the ethics application Ref: HEC 2013/05/LR.

As part of the transcription process we would now like to engage Merrill Corporation NZ to convert the audio interview dialogue to text. Previously the transcription has been executed by an individual in accordance with the conditions described in the ethics application amendment approved on the 27th March 2013. This person is no longer available to complete the work and so we have sort the professional services of Merrill Corporation NZ to complete the task.

To comply with the requirements of the University of Canterbury Human Ethics Committee, we request that once Merrill Corporation is engaged in the transcription work that the confidentiality of audio data is maintained by the existing confidentiality agreement in place between Merrill Corporation NZ and their employees.

In addition to this, Merrill Corporation NZ will not be made aware of the identities of the participants in any of the interviews. It will be requested that during transcription each speaker will be labelled with neutral identification such as person 1 and person 1 instead.

A pdf copy of the confidentiality agreement used by Merrill Corporation NZ has been provided by a representative of the company, and is attached to this email.

Please advise of any additional requirements that may be needed for this amendment to be approved.

Kind Regards
Katherine Yates

MERRILL LEGAL SOLUTIONS

Confidentiality Agreement

1. You understand that Merrill Legal Solutions ("MLS") is committed to preserving both its own confidential proprietary information and the confidential proprietary information of its Customers to the full extent permitted by law. Without prejudice to any other duty implied by law or equity, you shall not during the course of performing services for us, nor at any time thereafter, utilise for your own purposes or divulge or publish to any person whomsoever or otherwise make use of any trade secrets or any other confidential information concerning the business of MLS or any of our dealings or the business of our Customers or any of their dealings, which may have come to your knowledge during the course of providing services to us and you shall use your best endeavours to prevent the publication or disclosure by others of any such trade secret or other confidential information.

2. Confidential proprietary information will include, but is not limited to, information of a confidential or secret nature such as names, trade secrets, know how inventions, designs, processes, formulae, notations, improvements and financial information, concerning the affairs or business or products or services of MLS or any company within the Customer group or of any of their predecessors in business or of any third party to whom any company within the Customer group is under an obligation of confidence (including without limitation, suppliers, agents, distributors, employees or customers).

3. Clause 1 and Clause 2 shall not apply to any information or knowledge which might come into the public domain other than in consequence of your default.

4. For the avoidance of doubt and without prejudice to the generality of Clause 1, and Clause 2 the following is a non-exclusive list of examples of confidential information, which must be kept secret:-
   I. Unpublished price sensitive information relating to the securities listed on a Stock Exchange;
   II. Lists of customers or agents and details of contacts with customers or agents;
   III. Business strategies including those relating to pricing and marketing;
   IV. Lists of suppliers and details of contracts with suppliers;
   V. Information supplied in confidence by third parties including without limitation computer software, manuals, user guides and other documentation;
   VI. Technical information relating to the operation of the business of the Customer;
   VII. Names of individuals or companies.

5. This Agreement will remain valid after you cease to provide services to us.

I have read and understood the above and agree to be bound by its terms.

Signed: .... **Dated:** ....

Print Name: ....

UNIVERSITY OF CANTERBURY

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2013/05/LR – Amendment 5

22 July 2013

Katherine Yates
Department of Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Katherine

Thank you for your request for an amendment to your research proposal "Post-disaster assessment for hilly terrain exposed to seismic loading" as outlined in your email dated 19 July 2013.

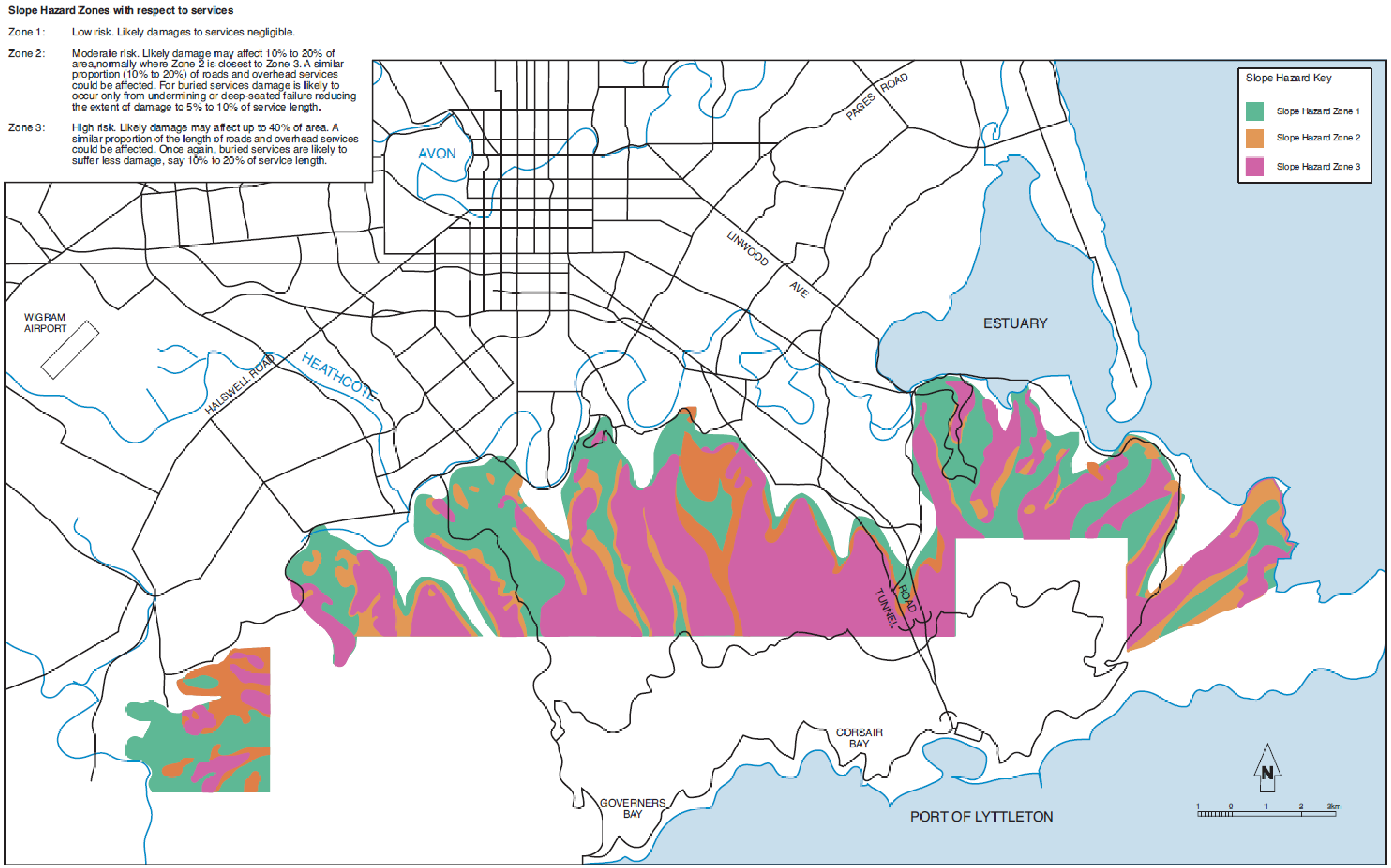
I am pleased to advise that this request has been considered and approved by the Human Ethics Committee.

Yours sincerely

Lindsey MacDonald
Chair, Human Ethics Committee

Appendix E – Hazard zone maps for Port Hills

Hazard zone map from (Centre for Advanced Engineering 1997).



Appendix F – Overview of New Zealand Civil Defence and Emergency Management framework

This Appendix aims to provide an overview of the Civil Defence and Emergency Management (CDEM) framework, and presents a brief overview regarding components of the CDEM response after the 4th September 2010 and 22nd February 2011 earthquakes that were discussed during research interviews.

The Canterbury Civil Defence and Emergency Management Group

The Canterbury Civil Defence and Emergency Management Group is a partnership between emergency services, local authorities and other organisations in the Canterbury Region. The aim of the group is to facilitate effective emergency management in the Canterbury Region under the Civil Defence and Emergency Management Act 2002 and the National Civil Defence and Emergency Management Plan 2006 (Sinclair 2008; Civil Defence and Emergency Management Group 2014).

In the event of an emergency which requires Civil Defence response, the Canterbury Regional Civil Defence and Emergency Management Group is responsible for understanding the impact of the event at a regional scale by gathering information from response organisations and communities in order to develop an action to support the local response. This could include obtaining external resources, providing information, coordinating resources and communicating with communities and the media (Civil Defence and Emergency Management Group 2014).

Although the Canterbury Regional CDEM is funded through Environment Canterbury (Ecan) and daily tasks and reporting are communicated to ECan, the group is accountable to a joint committee of local council Mayors and below this a joint committee of senior executives of local authorities and organisations involved in the CDEM group. Both groups are consulted when decisions regarding the functions and activities of the Canterbury CDEM Group are to be made (Civil Defence and Emergency Management Group 2014).

Levels of Civil defence and Emergency Management

In a typical Civil Defence and Emergency Management framework there are four layers to the response model. These are National level, regional level, local level and emergency services. Generally when a local or national state of emergency is declared each level of the emergency management framework is involved in the response to varying extents. Figure F1 shows the levels of the Civil Defence and Emergency Management contingent

Figure F.1: Typical four tiered emergency mangement framework

National Level CDEM

At the national level the National Crisis Management Centre (NCMC), which is situated in the basement of the Parliament buildings in Wellington, facilitates national and international coordination in the event of a national-scale emergency. The NCMC operates under the Central Government crisis management arrangements and is maintained in a constant state of readiness for activation. When the NCMC is activated it is staffed by personnel and liaison officers from the Ministry for Civil Defence and Emergency Management (MCDEM) and other supporting government agencies. Depending on the size of the emergency and the level of activation of the NCMC the involvement of the centre varies. In a national state of emergency the NCMC manages and controls the response to the event, however in a local scale emergency the NCMC will monitor and oversee the CDEM response. This can involve the collection of information and provide operational and logistical support where required (The Ministry of Civil Defence and Emergency Management 2014).

Regional Level CDEM

Beneath the National level response is the regional level civil defence response groups. In New Zealand there are sixteen regional level civil defence and emergency management response groups. Each of these groups oversees civil defence and emergency response within their region to a varying degree depending on the scale of the emergency. The regional level CDEM facilitates coordination and communication between local authorities involved in the group and aims to coordinate panning activities related to hazard and emergency management. Generally each Regional Civil Defence and Emergency Management Group will have their own Regional CDEM group plan in accordance with the CDEM act 2002 and the National CDEM plan 2006. The Regional Level CDEM will typically be based at their Emergency Coordination Centre (ECC) within the region.

Local Level CDEM

Each local authority or local council that is a member of the regional CDEM group will have their own emergency management capabilities. Typically each of the local councils will have staff that have been trained in civil defence response. When a local state of emergency is declared an Emergency Operations Centre (EoC) is set up. The EoC is used to coordinate the local level response and correspond with emergency services, the regional level CDEM and national level CDEM when required.

Emergency Services

The final level of the CDEM framework is the emergency services such as the Fire department, St Johns Ambulance and Police. These organisations deal with quotidian emergency incidents often without the coordination of high level CDEM response. However, in the event of a state of emergency the emergency services group set up their own coordination centre to coordinate the emergency services response, and communicate with local level and regional level CDEM.

Science and Civil Defence and Emergency Management (CDEM)

The National Civil Defence Emergency Management Plan (2006) outlines the role of science organisations such as GNS in emergency response. The capabilities of GNS are included in CDEM through a memorandum of understanding (MOU) with the Ministry of Civil Defence and Emergency Management (MCDEM). The MOU details the basis in which the GNS is to assist MCDEM in a crisis situation (The Ministry of Civil Defence and Emergency Management 2009). Part of the role of GNS in the National Civil Defence Emergency Management Plan (2006) is to provide monitoring information and notifications for earthquake and volcano hazards.

Professional engineers are included in the national civil defence plan through Institute of Professional Engineers (IPENZ) who maintain a register of professional able to provide their assistance during emergency response (The Ministry of Civil Defence and Emergency Management 2009).

Declaration of a state of emergency

The Civil Defence and Emergency Management Act 2002 has two levels of declaration of state of emergency; local and national. Declaration of a state of emergency enables the CDEM group controller to obtain the powers of the Civil Defence and Emergency Management Act 2002 in order to provide the necessary authority for protecting life and property in extraordinary emergency events (Ministry of Civil Defence and Emergency Management 2006). The benefits of this are increased coordination and ability to obtain resources when required.

Underpinning local and national level state of emergency declarations are five CDEM response levels that are detailed in the National CDEM Plan. This framework has been applied by most CDEM groups in New Zealand. Table F.1 has been adapted from the Declaration: Directors Guidelines for CDEM Sector [DGL 05/06] to show the five levels of CDEM response.

Table F.1: Levels of response for a CDEM Group – modified from (Ministry of Civil Defence and Emergency Management 2006)

Level	Description	Declaration Status
1	Single agency incidents with on-site coordination. Incidents generally maintained at a day-to-day level under the New Zealand Coordinated Incident Management System and statutory powers of the fire, police and ambulance	No Declaration
2	Multi-agency incidents with on-site, local coordination; these are managed by the incident controller of the relevant lead agency. Level 2 incidents involving CDEM groups do not require the coordination or powers resourced from the CDEM Act 2002.	No Declaration
3	A multi agency emergency led by an agency other that a CDEM group, or a state of local emergency at below CDEM Group-level (district or ward); at this level. CDEM Group support and coordination will be required and may be monitored by the National Controller.	Declaration of state of local emergency for a ward, part of a district or one or more local authorities within the CDEM Group
4	A multi-agency emergency with more significant consequences than in level 3; coordination may be required between agencies or areas or both; CDEM Group-level support and coordination is required; the actual or potential need for a declaration of a state of emergency by a CDEM Group requires consideration; national monitoring will occur and national support is available.	Declaration of state of local emergency for whole group area
5	A state of national emergency exists or the civil defence emergency is of national significance; at this level, coordination by the National Controller will be required.	Declaration of state of national emergency

Typically when a National State of Emergency is declared the required response to the emergency is outside the scope of local CDEM Group resources, and national resources are required to be drawn upon in the response and recovery phase.

CDEM response to the 4th September 2010 and 22nd February 2011 earthquakes during the Canterbury Earthquake Sequence

4th September 2010 earthquake

This local level CDEM response was overseen by the Canterbury Regional Civil Defence Group within the ECC. With the support of the Ministry for Civil Defence and Emergency Management (MCDEM) the Canterbury Regional CDEM Group took a role of coordination of resources across the Canterbury Region to support the local council responses and coordinated emergency welfare for communities. A research coordination office was set up at the Canterbury Regional ECC to coordinate daily research activities by scientists interested in studying the Greendale fault rupture and associated affects. This research coordination office provided an interface between emergency responders and researchers (Berryman 2012).

Communication was a crucial component for the coordination of the response between the local and regional level emergency response groups. During the response, local CDEM response was required to communicate their response activities through situation reports and participation in meetings at the ECC. Immediately after the earthquake the fluidity of the response was restrained by the lack of communication between local and regional CDEM, however, this improved as the response continued.

22nd February 2011 Earthquake

After the declaration of the National State of Emergency an Emergency Operation Centre (EoC) and an Emergency Coordination Centre (ECC) were established. In the immediate aftermath of the earthquake, communication between the ECC and the EoC was relatively strained despite the facilitation of communication through regular meetings and situation reports. At these meetings the EoC controller would provide situation reports which would detail the situations that the Emergency Operations Centre was dealing with, and present plans for dealing with the situation. Communication between the ECC and the EoC was also maintained through the presence of an Emergency Management Officer from a local authority which was placed within the EoC in an effort to encourage communication flow to the ECC.

The CDEM response coordination continued in accordance with the four tiered response model for the first two to three days after the earthquake (Figure F1). The four tiered response included emergency services, the Christchurch City Council EoC, the Canterbury Regional CDEM ECC and the NCMC and MCDEM. Days after the earthquake this response frame work was then altered by the National Controller who combined the local level and regional level CDEM groups at the Christchurch Art Gallery. This formed the Christchurch Earthquake Response Centre. Integration of local and regional CDEM took place because of the scale of the event, and because only one local authority had been affected. The composite CDEM response framework was divided into Operations and Planning and Intelligence (Figure F2).

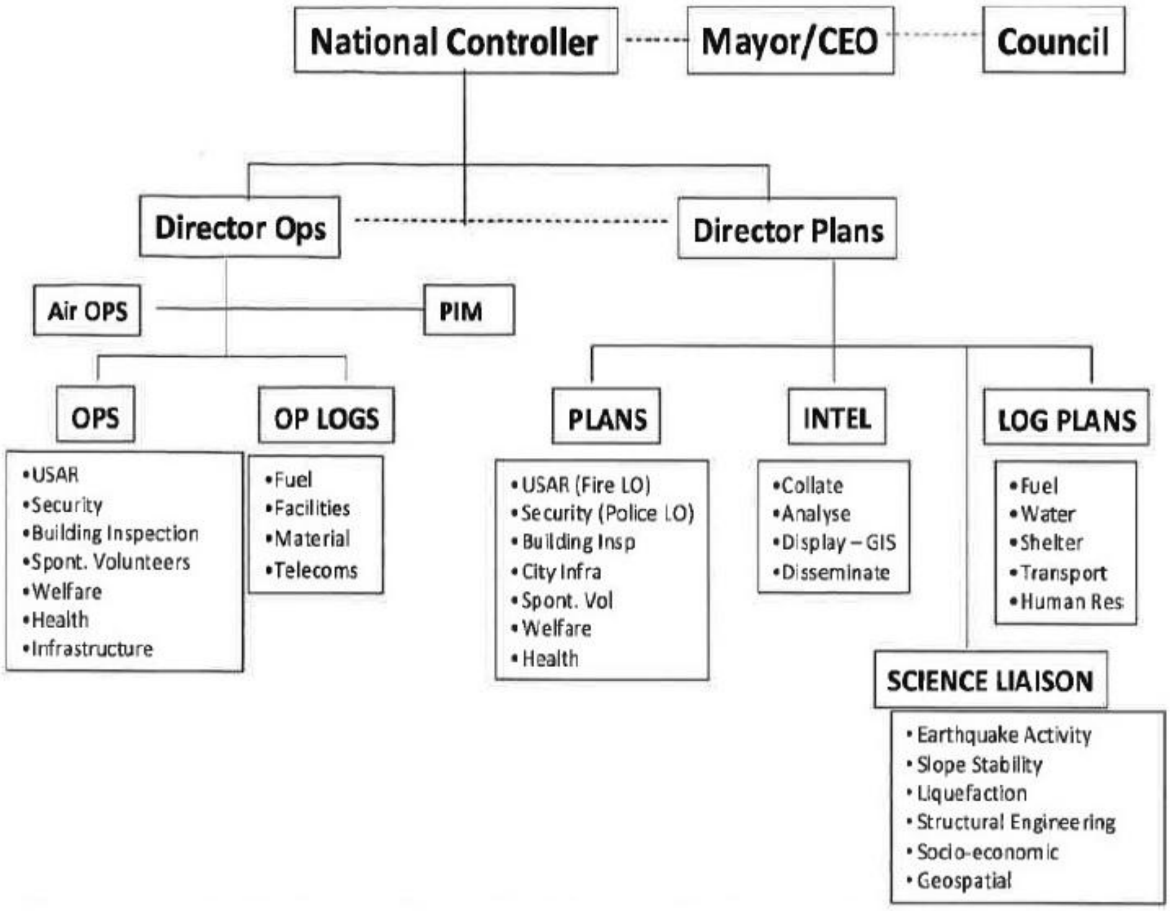


Figure F.2: Organisational structure for combined Christchurch Response Centre (Mclean et al. 2012).

Appendix G – Standard data collection spreadsheet

Christchurch City Council Civil Defence - 22 Feb 2011 Earthquake, Port Hills Geotechnical Hazard Management Steering Group

Prepared by			Comments		
Reviewed by			Comments		
Compilation Date	Phase: Response		Entered in database by	Date	GIS mapping updated by

				Potential Effect or Consequence			Likelihood or Time Frame					
No.	Location	Description of Affected Area, Lifeline, or Critical Infrastructure	Type of Mechanism	Classify Effect(s)	Scale of Potential Effect(s)	Importance Rating	Initiation / Progression of Mechanism	Initiation Rating	Hazard Exposure Scores	Treatment Plan Summary	Target Date	Completed
Unique database ref code	*Comment: Street Address(s), and / or GPS coords (Transverse Mercator). Include source and or affected areas if different.*	*Comment: Clearly describe and mark the affected area on the map such that GIS definition can follow. e.g.Describe the specific section of a lifeline or group of properties etc.*	*Comment: Select from Type categories below*	*Comment: Select from Effect categories below*	*Describe the current degree of exposure to loss of life (note current evacuation status) and lifelines or critical infrastructure. Consider rate of failure and note this is a current snapshot that may change in later phases*	*Select from Importance categories below*	*Comment: Describe the conditions or time scale under which the mechanism may progress to full failure*	*Select from Initiation categories below*	*Score = Import. Rating x Initiation Rating*	*Comment: Summarise your evaluation and proposed treatment action steps. Use a separate line for each progressive action. Include already completed hazard mitigation treatment actions as appropriate; i.e. evacuation.*		

Legend

-	-	-	-	Extreme Hazard ≥ 300	
L Localised failure of retaining walls or fill slopes with no evidence of large scale landslide instability.	**I** Inundation; including debris run out and boulder impact	**100** Extreme loss of life or exceptional safety / reliability required; e.g. nuclear reactor. PAR >100	**5** Imminent; likely to occur very soon under static conditions	Very High Hazard ≥ 150	
R Rockslides, Rockfalls, and Boulder Rolls.	**E** Evacuation; slumping, loss of support, lateral spreading etc	**50** Very high loss of life consequences or reliable post distaster functionality required. PAR =31-100	**4** Llikely to occur soon or after moderate rainfall or moderate after shock loading	High Hazard ≥ 80	
T Renting; i.e. tension cracking and/or relaxation colinear to topographyy		**20** High loss of life consequences or very great community impact. Resident PAR =6-30	**3** Expected to progress to failure following progressive relaxation / strain	Moderate Hazard ≥ 30	
C Complex large scale deformation, possibly consistent with structurally controlled landsliding (e.g horizontal and vertical displacement, or you're not sure).		**10** Medium loss of life consequences; normal individual buildings. Resident PAR =1-5	**2** Expected to occur after severe EQ or storm event	Low Hazard ≥ 10	
		1 Low - Not likely to endager life. Resident Population at risk (PAR) =0	**1** Unlikely to progress to failure within 6 months	Negligible Hazard <10	

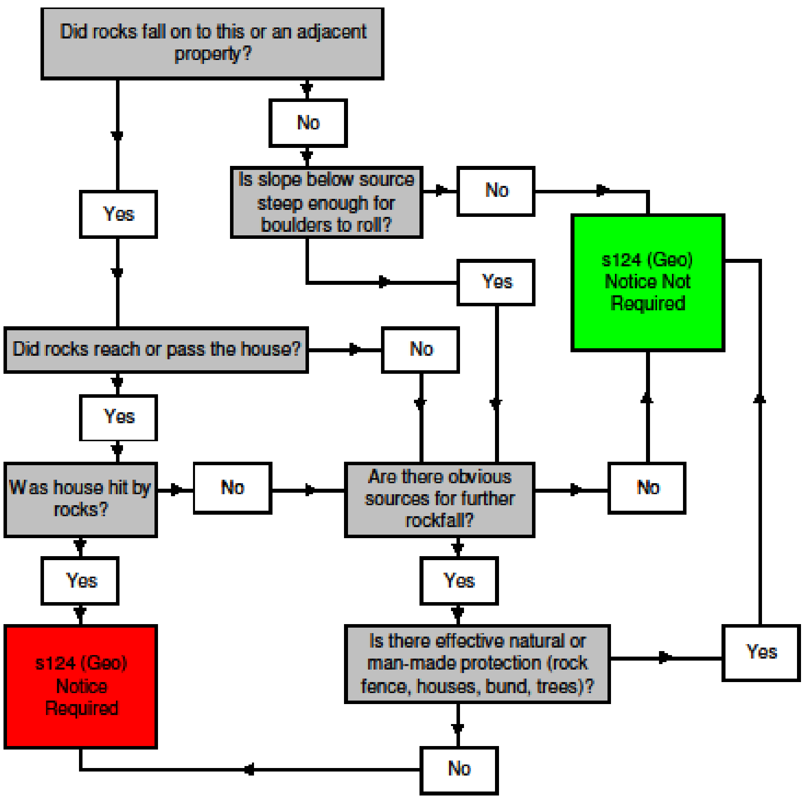
Appendix H – Rockfall hazard assessment flowchart

The s124 notice assessment flow chart has been referenced from (Macfarlane and Yetton 2013).

Port Hills Geotechnical Group
s124 (geo) Notice Application Decision Process - Boulder Roll

Address of property: ______________________ Review Date: ____________

Owner: ______________________ Valuation No: ____________



Check Yes/No boxes as applicable to lead to the decision.

Assessed by: ....

Checked by: ....

Comments:

Appendix I – Section 11 from ATC-20 guidelines

Guideline Development

The requirement for post-earthquake building safety evaluation guidelines was identified following the 1971 San Fernando, California earthquake by the California Governor's Office of Emergency Services and the Structural Engineers Association of California (NZSEE 2011). This led to the establishment of the United States Applied Technology Council (ATC) who in 1989 developed the first edition of ATC-20 *Procedures for Post-Earthquake Building Safety Evaluation* (Applied Technology Council 1995). The development of the guidelines was commissioned by government agencies and were first used after the 1989 Loma Prieta, California earthquake three weeks after the guidelines were published (NZSEE 2011).

The following pages are referenced from section 11 of the ATC-20 *Procedures for Post-Earthquake Building Safety Evaluation.*

11. Inspection of Geotechnical Hazards

11.1 Discussion

A number of geotechnical hazards can cause damage and threaten the safety of structures. For instance, large earthquake-induced foundation settlements or lateral spreading of soil beneath buildings due to liquefaction can severely damage structures, including those otherwise highly resistant to ground shaking. Similarly, massive ground movements associated with surface fault rupture can also damage, or even destroy, otherwise well-designed construction. This chapter deals with the recognition and evaluation of geotechnical hazards.

In postearthquake evaluation of buildings, in areas of obvious ground movement or other potentially hazardous geotechnical conditions, there are two fundamental safety questions to be answered:

1. Have ground movements disrupted the foundation and caused significant structural damage to the building?

2. Is ground movement or a hazardous condition likely to continue?

The first question can be answered by a structural engineer, and guidance is given in Chapters 6 through 10. The second question is best answered by geotechnical specialists, and some guidelines are given below.

11.2 Qualifications of Geotechnical Hazard Investigators

Investigators should be either geotechnical engineers or engineering geologists, preferably operating in teams of at least two persons. They should have experience in the technical areas under review and should be cognizant of the various types of earthquake-related ground movements that are damaging to structures, embankments, and earth dams.

11.3 Geotechnical Hazard Evaluation

The following is a list of geotechnical hazards that can pose a threat to structures along with recommended posting criteria. Inspection points for some of these hazards are illustrated in Figure 11.1.

The geotechnical guidelines given below require the use of judgment. Under some circumstances, the posting actions recommended (e.g., Unsafe) may not be warranted, and use of a less restrictive posting (e.g., Limited Entry, Area Unsafe) or other action may be appropriate.

1. **Surface Fault Rupture.** Faulting through a facility can result in both horizontal and vertical ground offsets. These displacements can cause massive distress to buildings (Figure 11.2). In addition, some fault movements produce secondary compressional or extensional ground displacements over a relatively wide area. These secondary deformations can compress or pull apart a building. Normally, fault movement is a one-time occurrence with each earthquake episode and will not occur again unless another earthquake occurs on the same fault in the same area. Postearthquake creep has occurred on several faults, however, and could cause additional damage.

Building Damaged by Fault Rupture....... UNSAFE

2. **Slope Failures.** Buildings can be damaged severely by slope failure. A structure located on unstable soil can suffer foundation, and subsequent structural, distress due to differential movement in the soil (Figure 11.3). Buildings and people can also be harmed by soil and debris from upslope failures (Figure 11.4). Aftershocks and even static loads may increase ground movements. The likelihood of continued movement must be assessed by the geotechnical hazard evaluators (Figure 11.5).

Slope Failure Has Caused Foundation Damage or Loss of Foundation Support.. UNSAFE

Slope Movement Continuing Under Static Conditions.......................... AREA UNSAFE

Building in Active Slope Failure Zone .... UNSAFE

Building in Path of Debris, Including Rock Fall, from Active Slope Failure Zone..UNSAFE

Retaining Wall Leaning Outward 5° (1:12 slope) or More to Vertical...AREA UNSAFE

3. **Other Differential Ground Movements.** These movements may be horizontal or vertical and may be caused by liquefaction (Figures 11.6 and 11.7) and vibratory compaction. Aftershocks may cause continued movement.

Building Damaged by Ground Displacement...UNSAFE

Ground Fissures and Scarps More Than 4" Wide Near Buildings..................UNSAFE

4. **Earth Dam or Reservoir Movement.** Sudden failure of an earth dam or reservoir can be accompanied by a water wave and rapid flooding downstream. Cracks, seepage, or failures in embankments of dams or reservoirs in the vicinity of populated areas must be taken seriously. While not the primary subject of this report, the following concerns should be considered when the damage- assessment teams encounter dams and reservoirs in populated areas.

Large Cracks, Increased Seepage, or Embankment Failure in Earth Dam ....AREA UNSAFE

Overtopping of Dam by Wave......AREA UNSAFE

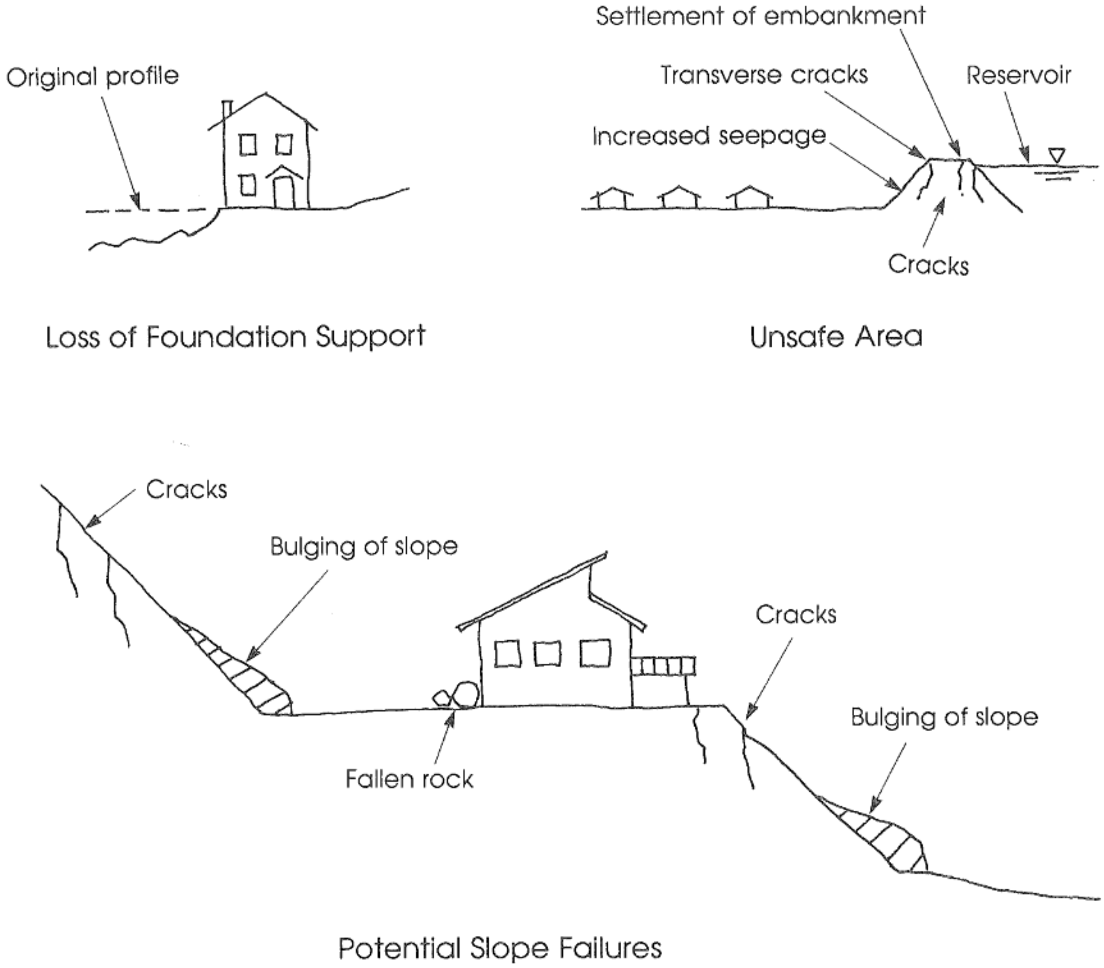


Figure 11.1 Inspection points for some geotechnical hazards.

Figure 11.2 House damaged by ground displacements caused by surface faulting from the 1971 San Fernando, California, earthquake.

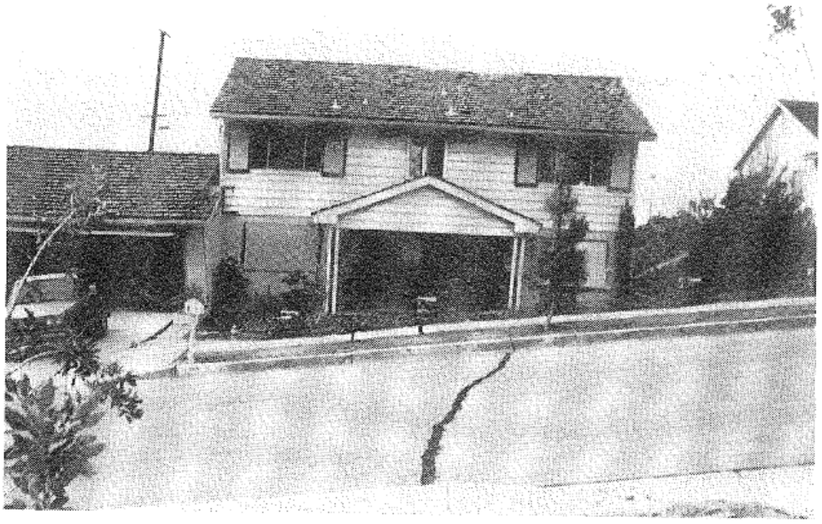


Figure 11.3 House and street damaged by several inches of landslide displacement caused by San Fernando earthquake.

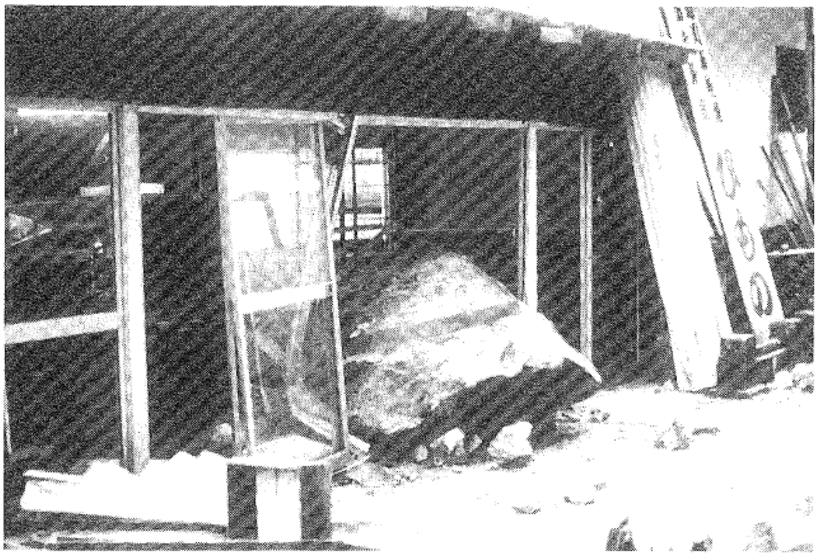


Figure 11.4 *Damage to store front caused by rock fall.*

Figure 11.5 *Whenever large slides appear to threaten the safety of buildings, geotechnical specialists should assess the possibility of further movement.*

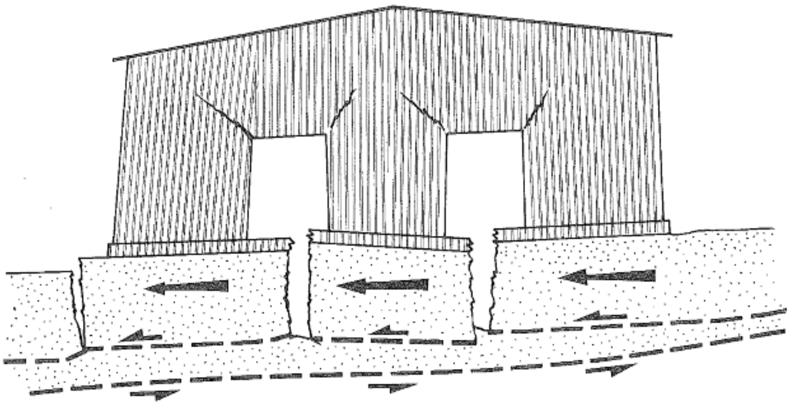


Figure 11.6 *Drawing depicting lateral spread of soil and subsequent damage to San Fernando Valley Juvenile Hall during 1971 San Fernando earthquake.*

Figure 11.7 *Damage to the San Fernando Valley Juvenile Hall caused by lateral spreading.*

Appendix J– Non-Disclosure Agreement (NDA)

Some of the information collected for this thesis was obtained from geotechnical consultancies in the Port Hills Geotechnical Group (PHGG). Because consultancies within the PHGG were under contractual agreement with the Christchurch City Council (CCC) during the time of their involvement in the response in the Port Hills, CCC requested a non-disclosure agreement with the University of Canterbury and Environment Canterbury to maintain confidentiality of source data. The NDA is attached in Appendix J as a record.

Non-Disclosure Agreement

between

Christchurch City Council

and

University of Canterbury

and

Environment Canterbury

and

Katherine Yates

Non-Disclosure Agreement

Date: 2013

Parties

1. **Christchurch City Council** ("the Discloser")
2. University of Canterbury ("UC")
3. Environment Canterbury ("ECan")
4. Katherine Yates ("Katherine")

(2, 3, and 4 above, together the "Recipients")

Background

A. The Discloser has agreed to disclose certain information to the Recipients in relation to the Purpose described below.

B. This agreement sets out the terms on which such disclosure will be made.

This agreement records

1. Interpretation

1.1 In this deed:

"**Confidential Information**" means all information and data of whatever nature, directly or indirectly concerning the Purpose, whether such information and data has been provided by the Discloser and whether or not it relates directly or indirectly to the Discloser, including, without limitation:

a. any intellectual property, including any opinion, projection, idea, intranet information, concept, process, procedure, plan, design, programme, study, data, report, know-how, expertise or other such property; and

b. any document, data, statement, analysis, opinion, projection, forecast, report, note, notebook, drawing, manual, letter or such other material whether in a permanently visible form or not;

but excludes:

a. information that as of the date of disclosure is in the public domain or subsequently enters the public domain without fault on the part of the Recipients;

b. information that at any time is received in good faith by the Recipients from a third party which was lawfully in possession of and had the right to disclose the information and did so without any limitation on confidentiality.

"**Person**" includes a natural person, individual, firm, company, corporation, association or other entity, whether incorporated or not.

"**Purpose**" means the development, creation and publication of a Master's Thesis (including all drafts) titled "Post-disaster Risk Assessment for Hilly Terrain exposed to Seismic Loading", ("Master's Thesis") by Katherine, with co-supervisors Dr Thomas Wilson and Dr Marlene Villeneuve ("the co-supervisors") under the supervision and auspices of UC and funding from ECan (but not otherwise.by third parties).

2. Confidentiality undertakings

2.1 The Recipients each agree to receive the Confidential Information in the strictest confidence and to keep the Confidential Information strictly confidential and to take all steps to prevent any unauthorised use or disclosure of the Confidential Information. Without limiting the preceding sentence, the Recipients will not at any time:

a. disclose, distribute or permit to be disclosed or distributed the Confidential Information to any Person (including any officer, employee, agent or advisor of or to the Discloser); or

b. in any way use the Confidential Information for any purpose other than the Purpose; or

c. assert any rights of any nature in respect of, or contest the Discloser's ownership of, the Confidential Information.

2.2 The Recipients will at all times maintain adequate security measures to prevent the Confidential Information being used or disclosed other than as permitted by this Agreement.

3. Receipt and assessment of confidential information

3.1 The Recipients acknowledge that the Confidential Information will be provided to each of them solely for the Purpose and shall not be used by the Recipients for any other purpose. The Confidential Information will be supplied solely via the Discloser's consultants and the Recipients acknowledge that a process will need to be followed by the Discloser in providing the Confidential Information to the Recipients. For the purposes of clarity, the Recipients agree that they shall not be entitled to conduct interviews with, or seek to obtain Confidential Information from, any of the Discloser's employees.

3.2 The parties acknowledge that certain Confidential Information has already been obtained by the Recipients, however there are two remaining interviews to be carried out with the Discloser's consultants. The Discloser agrees to allow these interviews to take place, provided that the Discloser is entitled to view the questions to be asked in advance of the interviews and is given the opportunity to view the final responses given by the Discloser's consultants to the Recipients.

3.3 The Recipients shall not copy or reproduce any Confidential Information in any way, except with the prior written consent of the Discloser.

3.4 The Recipients agree that they are solely responsible for their own assessment and evaluation of the Confidential Information and the Discloser does not warrant or represent the accuracy, adequacy or completeness of any of the Confidential Information.

3.5 The Recipients acknowledge that this agreement creates no obligation on the Discloser to give any particular information, or to contract with the Recipients, or otherwise engage or enter into any arrangement of any sort with the Recipients.

4. Disclosure required by law

4.1 If any of the Recipients is legally required to disclose any Confidential Information, that Recipient will:

a. immediately notify the Discloser of such requirements; and

b. fully co-operate with all legal actions taken by the Discloser to avoid or limit such disclosure.

4.2 If the Discloser cannot avoid such disclosure, the Recipient will:

a. only disclose such portions of the Confidential Information as are legally required to be disclosed by law; and

b. use its best endeavours to obtain assurances that such information will be treated as confidential by any Person to whom it is disclosed.

5. Indemnity

5.1 The Recipients will indemnify the Discloser from and against all actions, claims, costs (including all reasonable legal, accounting, and other professional fees), demands, expenses, liabilities, losses, payments and proceedings whatsoever incurred or suffered by them which arise from or by virtue of the unauthorised disclosure or use of the Confidential Information by the Recipients any of their respective officers or employees or any such Persons otherwise being in breach of any of the provisions of this agreement.

5.2. The Recipients total aggregate liability to the Discloser in connection with this agreement will not under any circumstances exceed 2 times the total remuneration specified in the Student Research Agreement dated the 4^{th} of December 2012.

6. Remedies

6.1 In addition to any other rights or remedies to which the Discloser may be entitled under this agreement or otherwise at law, the Recipients, in recognition of the injury which could be caused to the Discloser if Confidential Information is disclosed and in recognition that damages may be an insufficient remedy for such a breach of confidence, consents to the issue of an injunction or other order specifically enjoining the Recipients or any other Person from engaging in any action in breach of the terms of this agreement.

7. Non-Assignment

7.1 The Recipients agree not to assign, transfer or otherwise dispose of all or any of its rights under this agreement or to deal with those rights on behalf of any other person.

8. Term

8.1 The obligations as to confidentiality and use of the Confidential Information in this agreement remain in full force and effect for a period of one year from the date of this agreement.

9 Embargo

9.1 There shall be an embargo on the publication by any of the Recipients (including the co-supervisors) of the Master's Thesis or any Confidential Information during the term of this agreement as set out in clause 8. On the expiry of the term, the Discloser shall provide a final sign-off approving the release and publication of the Master's Thesis. Such approval from the Discloser may be given in its sole discretion

9.2 In the event that Katherine wishes to present on any aspect of her Master's Thesis during the embargo period, she shall be required to first obtain permission from the Discloser. The Discloser may grant permission at its sole discretion to the release of all or some of the Confidential Information. Where such permission is granted by the Discloser, the Discloser shall be named as a joint author of the work presented.

10. General

10.1 No waiver by the Discloser of any provision of or right, remedy or power of the Discloser under this agreement, and no amendment to this agreement will be effective unless it is in writing signed by the Discloser. Any such waiver will be effective only in the specified instance and for the specific purpose for which it is given. No failure or delay by the Discloser to exercise any right, remedy or power under this agreement or to insist on strict compliance by the Recipients with any obligation under this agreement, and no custom or practice of the parties at variance with the terms of this agreement, will constitute a waiver by the Discloser of any of its right to demand exact compliance with this agreement.

10.2 If any provision of this deed becomes invalid and unenforceable for any reason, the remaining provisions will remain valid and enforceable.

10.3 This agreement is governed by and in accordance with the laws of New Zealand. The Recipients submit to the exclusive jurisdiction of the courts of New Zealand in the interpretation and enforcement of this agreement.

Signed by the parties

Signed by **Christchurch City Council** as Discloser by its duly authorised signatories:

Authorised person's signature

Signed by **Katherine Yates** as Recipient:

Katherine Yates

Signed by **University of Canterbury** as Recipient by its duly authorised signatory:

Authorised person's signature

Signed by **Environment Canterbury** as Recipient by its duly authorised signatory:

Authorised person's signature

Appendix K – Glossary

Annual Individual Fatality Risk - The probability (likelihood) that a particular individual will be killed in any year at their place of residence as a result of rockfall or cliff collapse (Massey et al. 2012a; Massey et al. 2012b).

Elements at risk - the people, buildings and structures, infrastructures, economic activities, public services, or any other defined values exposed to hazards in a given area (Glade et al. 2004).

Exposure - as the length or proportion of time that a person, building or other entity runs a risk (Alexander 2002).

Landslide inventory – An inventory of the location, classification, volume, activity and date of occurrence of landsliding

Landslide susceptibility– a quantitative or qualitative assessment of the classification, volume, a spatial distribution of landslides which exist or potentially may occur in an area

Qualitative risk analysis – an analysis which uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur (Fell et al. 2005)

Quantitative risk analysis – an analysis based on numerical values of the probability, vulnerability and consequences, and resulting in numerical value of risk (Fell et al. 2005)

Risk - as the measure of probability and severity of an adverse affect to life, health, property, or the environment (ISSMGE 2004)

Risk Avoidance - An informed decision not to become involved in a risk situation (AGS 2000)

Risk Reduction - A selective application of appropriate techniques and management principles to reduce either likelihood of an occurrence or its consequences, or both (AGS 2000)

Risk Transfer **-** Shifting the responsibility or burden for loss to another party through legislation, contract, or other means. Risk transfer can also refer to shifting a physical risk or part thereof elsewhere (AGS 2000).

Vulnerability - the degree of loss to a given element or se of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude (Glade et al. 2004)